ENERGY
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7

FOR INDUSTRY
COMMERCE
AND INSTITUTIONS

# Process furnaces, dryers and kilns

Energy, Mines and Resources Canada
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Canada

# PREFACE

Much has been learned about the art and science of managing energy during the past decade. Today, energy management is a seriously applied discipline within the management process of most successful companies.

Initially, in the early 1970's, energy conservation programs were established to alleviate threatened shortages and Canada's dependency on off-shore oil supplies. However, dramatic price increases quickly added a new meaning to the term "energy conservation" — reduce energy costs!

Many industrial, commercial and institutional organizations met the challenge and reduced energy costs by up to 50%. Improved energy use efficiency was achieved by such steps as employee awareness programs, improved maintenance procedures, by simply eliminating waste, as well as by undertaking projects to upgrade or improve facilities and equipment.

In order to obtain additional energy savings at this juncture a greater knowledge and understanding of technical theory and its application is required in addition to energy efficiency equipment itself.

At the request of the Canadian Industry Program for Energy Conservation, the Commercial and Institutional Task Force Program and related trade associations, the Industrial Energy Division of the Department of Energy, Mines and Resources Canada, has prepared a series of energy management and technical manuals.

The purpose of these manuals is to help managers and operating personnel recognize energy management opportunities within their organizations. They provide the practitioner with mathematical equations, general information on proven techniques and technology, together with examples on how to save energy.

For further information concerning the manuals listed below or regarding material used at seminars/workshops including actual case studies, please write to:

Industrial Energy Division
Energy Conservation Branch
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Materials Handling and On-Site Transportation Equipment
Architectural Considerations
Process Furnaces, Dryers and Kilns.

Minister of Supply and
Services Canada 1985
Cat. No. M91-6/7E
ISBN 0-662-14159-8

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# INTRODUCTION

Furnaces, dryers and kilns are used extensively in industry for diverse applications such as melting and heating metal, evaporating water or solvents, and manufacturing lime for the cement and pulp industries. Much of this equipment was installed when fuel was relatively cheap, and little or no consideration was given to energy management. Even today, first cost and production capability are frequently the prime criteria for the selection of equipment, with energy management relegated to a minor role.

The high cost of fuel today demands a greater awareness of energy management techniques which can be applied to existing and new installations. Substantial savings in energy and dollars can be realized by the application of these techniques. In many instances the returns on the capital invested make the application of energy management techniques one of the most attractive investment opportunities available to industry.

This module shows how to apply energy management techniques to save energy and dollars in the installation and operation of process furnaces, dryers and kilns.

## Purpose

The purpose of this module is as follows.

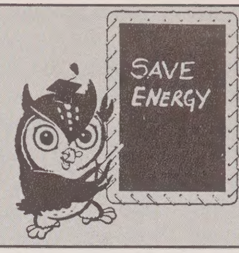
- Provide a brief introduction to the subject of furnaces, kilns, and dryers as used in industry.
- Generate an awareness of the potential energy and cost savings possible with the implementation of Energy Management Opportunities.
- Describe methods of determining energy and cost savings with calculations and worked examples.
- Suggest Energy Management Opportunities that can be studied to determine potential energy and cost savings.

## Contents

The contents of this module have been subdivided into the following sections.

- *Fundamentals*. This section contains a brief description of process furnaces, dryers and kilns. The combustion process, and the transfer of heat from the energy source to the product is described. The calculation of energy losses and the measurement of energy input and losses are also covered. Control systems are introduced, with a description of their role in energy management. The concept of an energy audit is introduced with suggestions for goals and methods of implementation.
- *Equipment and Systems*. This section describes types of fuel-fired and electrically-heated furnaces, dryers and kilns. The energy management possibilities of the various types are identified.
- *Energy Management Opportunities.* This section suggests specific Energy Management Opportunities, with worked examples illustrating the determination of energy savings and the resulting returns on expenditures.

# FUNDAMENTALS

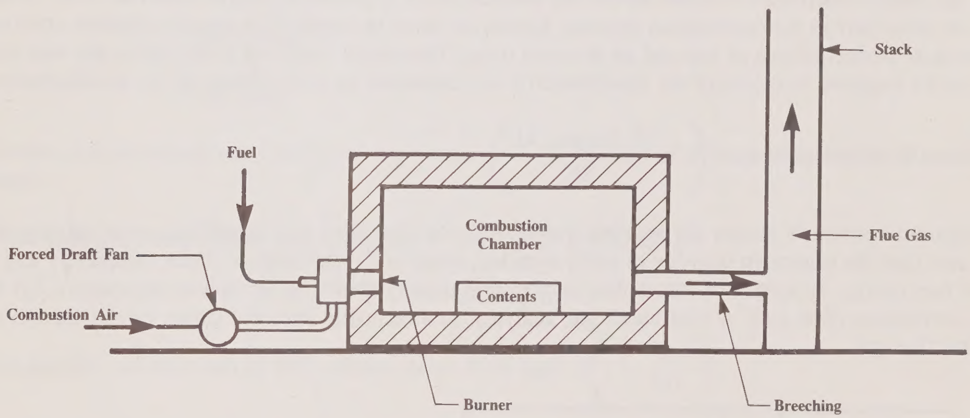



Process furnaces, dryers, and kilns are used extensively in many industries for a wide variety of applications involving the addition of heat. The following is a selection of some of these uses.

- Heating of metals for heat treatment or forging.
- Melting of metals for casting.
- Manufacturing of bricks and ceramics.
- Evaporation of water in the drying of wood, malt and other products.
- Evaporation of solvents in the manufacture of products such as chemicals and carbon electrodes, and in the drying of paint.
- Manufacture of lime by the heating of limestone.

## General Design

The basic components of a fuel fired furnace are shown in Figure 1.




**Fuel Fired Furnace**
Figure 1

### Fuel System

In all applications of furnaces, dryers, and kilns heat is produced from the combustion of fuel or by the use of electrical energy. This heat is transferred to the product in a controlled manner to suit the product requirements. This could be metal heated to a specific temperature, metal completely melted but not overheated, water evaporated to produce a specific per cent dryness, or the complete conversion of limestone to lime.

If heat is produced by the combustion of fuel, the furnace, dryer or kiln will have a combustion chamber where the fuel is burned. The fuel is introduced into the combustion chamber at the burner, simultaneously mixed with air and ignited. The fuel is usually natural gas or fuel oil, but coke-oven or refinery gas produced in another part of a plant may also be used. The product may be exposed directly to the heat generated in the combustion chamber, or indirectly through a heat exchanger so that the product is not directly exposed to the combustion gas.

Electric furnaces produce heat by passing electricity through a series of resistance heaters. Since there is no combustion of fuel, the furnace can be totally enclosed to reduce the heat losses. The heat input can be readily controlled by switching the resistance heaters on and off.

The cost of electricity and fuels such as oil and gas varies widely. The efficiency of the heat generating process must also be taken into consideration when comparing energy sources.

The burner system is designed to provide adequate mixing of fuel and combustion air with a flame shape as required by the furnace design. Multiple burners may be installed, to provide a temperature pattern within the furnace. An example would be a reheating furnace for large steel billets, which may be divided into preheating, heating and soaking zones with each zone operating at a different temperature.

The appearance of the burner flame can be a guide to correct combustion conditions. Setting up the burner requires some experience. The appearance of the flame should be checked for future reference after an experienced furnace engineer has performed this task. In general terms, a natural gas flame should be clear or slightly blue in colour while an oil flame should be a light brown or yellow colour. A short blow-torch shaped flame indicates too much air, whereas a long lazy smoky flame indicates too little air. These observations may have to be modified if the furnace application requires unusual combustion conditions.

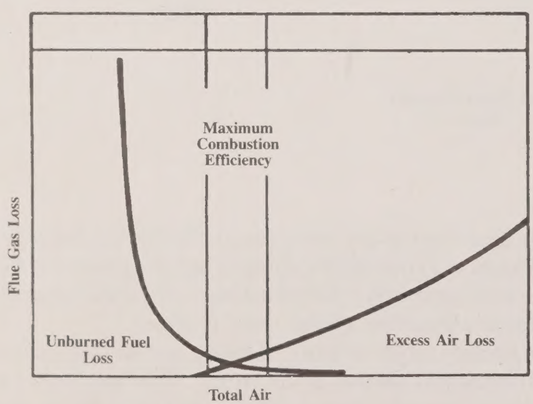
The quantity of fuel needed to generate a specific amount of heat depends on the heating value of the fuel. Heating value is the amount of heat generated when a fixed quantity of fuel is completely burned. The normal units are megajoules per cubic metre ($MJ/m^3$) for gaseous fuels, megajoules per litre (MJ/L) for liquid fuels, and megajoules per kilogram (MJ/kg) for solid fuels. The heating value of a fuel can usually be obtained from the fuel supplier, or the values given in Appendix C can be used with sufficient accuracy for most purposes.

## Combustion Air System

Stoichiometric air represents the amount of air required for complete combustion with the perfect mixing of the fuel and air. Stoichiometric air is sometimes called theoretical air. If perfect mixing is achieved, every molecule of fuel and air takes part in the combustion process. Excess air must be supplied to ensure complete combustion of the fuel because perfect mixing of fuel and air does not occur. Percentage excess air is defined as the total amount of combustion air supplied in excess of the stoichiometric air, expressed as a percentage of the stoichiometric air.

$$\text{Total air} = \text{Stoichiometric air} \times \left(1 + \frac{\%\ \text{Excess Air}}{100}\right)$$

The minimum amount of excess air required varies with the fuel used and the efficiency of mixing the air and fuel. If less than the minimum quantity of air is supplied, some of the fuel will not burn completely and there is a waste of fuel energy. Evidence of incomplete combustion usually shows up as carbon monoxide (CO) in the products of combustion (flue gas). A continuous gas analyzer, or a manually operated Orsat, can be used to check for CO in the flue gas.




**Zone of Maximum Combustion Efficiency**
Figure 2

Too much air also wastes energy. The gases leaving the furnace are hot and contain heat energy. If excessive amounts of air are supplied to the furnace, the excess will also be heated. The effect on heat losses of varying the amount of air supplied to the furnace is shown in Figure 2. The minimum losses occur when the amount of air supplied is slightly greater than the "stoichiometric" amount.

The weight or volume of each element or compound in the fuel is required to determine the stoichiometric air. Refer to Combustion, Module 5, for an example. It is often inconvenient to determine stoichiometric air in this manner, as in many instances the precise fuel analysis is unknown or varies. A more convenient method is to determine the quantity of air per unit of heat in the fuel, i.e. kilograms of air per gigajoule of heat in the fuel as fired (kg/GJ). Expressed in this manner, the stoichiometric air required for common types of fuel is almost constant. Table 1 provides values for several different types of fuel which may be used in furnaces.

It may be suspected that a supply air fan, air inlet louvres, ducting or the air flow control method is inadequate. Knowledge of the required amount of furnace combustion air enables checking the adequacy of the air supply system. The combustion air requirements can be calculated and compared to the capacity of the components in the air supply system.

*Example:*The total combustion air requirements for a furnace using 150 $m^3/h$ of natural gas when operating at 10 per cent excess air can be calculated as follows:

From Table 1, the combustion air required at 0 per cent excess air is 318 kg/GJ.

From Appendix C, the heating value of natural gas is 37.2 $MJ/m^3$.

$$\begin{aligned}\text{Total heat input} &= \text{Fuel consumption x Fuel heating value.}\\ &= 150\ m^3/h \times 37.2\ MJ/m^3\\ &= 5580\ MJ/h\\ &= 5.58\ GJ/h\end{aligned}$$

Combustion air requirement at 0 per cent excess air is the amount of air required per unit of heat input times heat input.

$$\begin{aligned}\text{Combustion air required at 0\% excess air} &= 318\ kg/GJ \times 5.58\ GJ/h\\ &= 1774\ kg/h\end{aligned}$$

$$\begin{aligned}\text{Combustion air required at 10\% excess air} &= 1774\ kg/h \times \left(1 + \frac{10}{100}\right)\\ &= 1951\ kg/h\end{aligned}$$

It is customary to express air and gas flow rates in volumetric units of cubic metres per hour ($m^3/h$). Since air and gas densities vary with temperature and pressure, it is necessary to specify standard conditions for the conversion of mass flow to volumetric flow. In the SI system the standard conditions are 20°C and 101.325 kPa(absolute), and the density of air is 1.204 $kg/m^3$.

$$\begin{aligned}\text{Combustion air} &= \frac{1951\ kg/h}{1.204\ kg/m^3}\\ &= 1620\ m^3/h \text{ at standard conditions.}\end{aligned}$$

*Example:*Combustion air requirements for a furnace using 700 L/h of No. 6 fuel oil, at 15 per cent excess air can be calculated. From Table 1, theoretical combustion air is 327 kg/GJ. From Appendix C, heating value of No.6 fuel oil with 2.5 per cent sulfur is 42.3 MJ/L (sulfur content can usually be obtained from the fuel supplier).

$$\text{Combustion air requirements} = \frac{700\ \text{L/h} \times 42.3\ \text{MJ/L} \times 327\ \text{kg/GJ} \times 1.15}{1000\ \text{MJ/GJ}}$$

$$= 11\ 135\ \text{kg/h}$$

$$\text{or } \frac{11\ 135\ \text{kg/h}}{1.204\ \text{kg/m}^3}$$

$$= 9248\ \text{m}^3\text{/h at standard conditions.}$$

Combustion air can be supplied to the equipment by natural or forced draft systems. Natural draft uses the negative pressure (draft) produced by the furnace stack to draw combustion air into the furnace and the resulting flue gases out of the furnace. The most common example of this is the ordinary domestic gas furnace. Natural draft is usually applied only to small furnaces with less than about one GJ/h heat input.

There are several disadvantages related to natural draft firing. The amount of combustion air drawn into the furnace cannot be controlled accurately and the fuel and air mixing is inefficient. This means that higher levels of excess air must be maintained to ensure that complete combustion is achieved under all conditions. The furnace pressure is always negative which allows air to leak into the furnace, and create additional flue gas volume and heat losses.

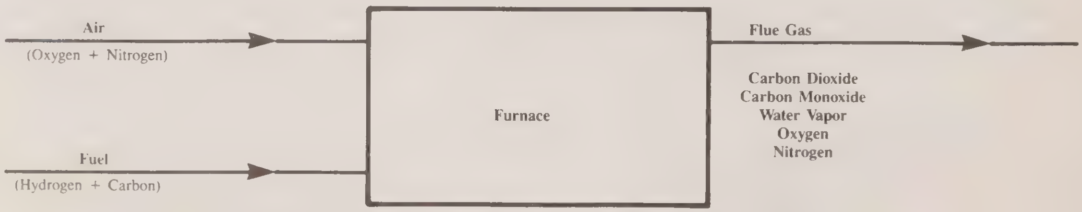
Forced draft firing uses a fan to supply combustion air to the equipment. Air flow is regulated by means of dampers so that accurate control of the proportion of air to fuel for various firing rates is possible. A common method used to achieve this is to operate the fuel valve and the damper with a common mechanical linkage. Some form of adjustable cam is used to vary the relative positions of the fuel valve and damper to provide proper fuel/air ratios at all firing rates.

The combustion air fan also provides better mixing of the fuel and the air. The air is introduced into the furnace around the burner(s) and turbulence can be created by vanes which produce a swirling motion in the air as it enters the furnace. A high pressure drop between the air supply and the furnace is required to produce turbulence, and this can only be achieved with a forced draft system. These advantages mean that the excess air for a forced draft system can be lower than for natural draft firing, with resulting lower heat losses to the flue gas.

Forced draft firing permits a slightly positive furnace pressure at all times. Leaks will then be from the furnace outwards which may lead to a dangerous situation when a furnace door is opened. Therefore, it is desirable to control furnace pressure at a slight positive value of not more than about 10 pascals. This is normally achieved by regulating a damper in the breeching between the furnace flue gas exit and the base of the stack. It may not be possible to maintain furnace pressure as low as desired if heat recovery equipment is installed in the flue gas system or if the stack provides insufficient draft.

## Excess Air

The actual percentage of excess air supplied to the furnace is one of the most informative items of information to the furnace operator. The most accurate way of determining this is to analyze the flue gas leaving the furnace.



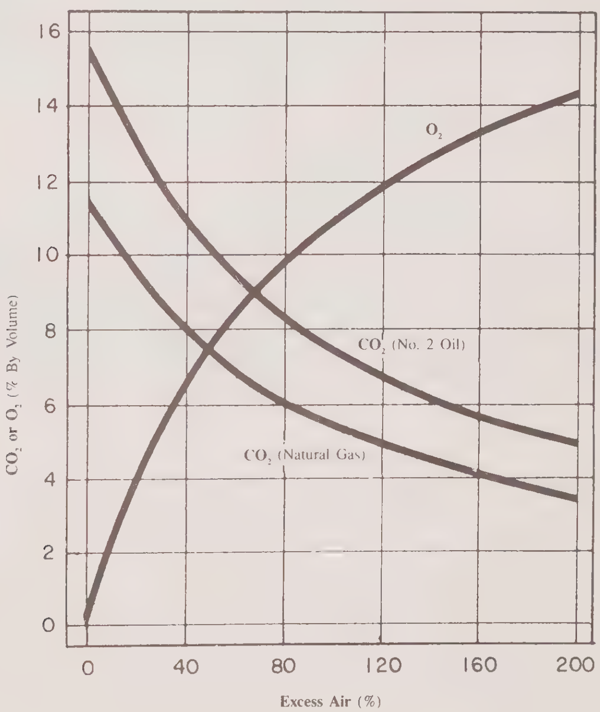

**Combustion Process**
Figure 3

## Flue Gas Analysis

A furnace in which heat is produced by the combustion of fuel can be considered to have fuel and combustion air as inputs, and flue gas as the output (Figure 3). Practically all fuels used in furnaces are hydrocarbons which contain the elements hydrogen and carbon. Although some fuels contain other constituents they are not usually important to the combustion process. The hydrogen in the fuel burns to form water vapor, and the carbon burns to form carbon dioxide ($CO_2$), or a mixture of carbon dioxide and carbon monoxide (CO). Air contains nitrogen ($N_2$) as well as oxygen ($O_2$). The $N_2$ does not take part in the combustion process, except for the formation of small quantities of nitrogen oxides ($NO_X$).

The major constituents of the products of combustion are water vapor, $CO_2$, CO, $N_2$, and any excess $O_2$ left over from the combustion process. Not all of the constituents will be present in all instances. The presence of CO indicates incomplete combustion.

Flue gas analysis can be determined by the use of a continuous analyzer or by periodic sampling. The sample should be taken as close to the furnace exit as possible to reduce air infiltration errors. Some continuous analyzers measure $O_2$ content and record or indicate the results. Other continuous analyzers measure the combustibles content of the flue gas, which is mostly CO but may also include some unburned fuel in gaseous form. If a continuous flue gas analyzer is not available, a sample of the flue gas can be taken and analyzed with the use of an Orsat. The Orsat determines the percentage by volume of $O_2$, $CO_2$, and CO in the flue gas. The remaining gas is assumed to be $N_2$, plus a small quantity of water vapor which did not condense out of the sample. There are other manually operated analyzers available which measure either $CO_2$ or $O_2$ in the flue gas. These are simpler to use and can be useful as a cross check against an Orsat.




**Excess Air Versus Flue Gas Analysis**
Figure 4

## Determination of Excess Air

Flue gas analysis provides sufficient data to calculate the excess air to the furnace. In most furnaces, CO is absent or very low because of high levels of excess air. For natural gas or fuel oil firing with no CO in the flue gas the per cent excess air can be determined from Figure 4. If other fuels are used or if CO is present, the following equation can be used:

$$\text{Excess Air} = \frac{O_2 - 0.5CO}{0.2682N_2 - (O_2 - 0.5CO)} \times 100$$

where, $O_2$ = oxygen by volume in flue gas (%)

$CO$ = carbon monoxide by volume (%)

$N_2$ = nitrogen by volume (%)

*Examples:* The flue gas analysis by volume on a furnace burning natural gas gives the following results:

$O_2$ = 9.8%

$CO_2$ = 6.2%

$CO$ = 0%

From Figure 4, excess air is approximately 79 per cent. This number can be compared to the following calculation.

$\%N_2 = 100\% - (9.8\% + 6.2\% + 0\%)$

$= 84\%$

$$\text{Excess Air} = \frac{9.8\% - (0.5 \times 0\%)}{(0.2682 \times 84\%) - [9.8\% - (0.5 \times 0\%)]} \times 100$$

$= 77\%$

This value is very high for a furnace burning natural gas, and the possibility of reducing the excess air level should be investigated.

Another example will provide greater familiarity with the calculation procedures. A furnace is burning coke-oven gas with the following flue gas analysis.

$O_2$ = 2.1%

$CO_2$ = 10%

$CO$ = 0%

$N_2$ = 87.9% (by difference)

The equation should be used to calculate the excess air since Figure 4 is not applicable for coke-oven gas.

$$\text{Excess Air} = \frac{2.1\%}{(0.2682 \times 87.9\%) - 2.1\%} \times 100$$

$= 9.8\%$

This excess air is quite acceptable for a furnace burning coke-oven gas.

In a furnace burning natural gas with a deficiency of air, the flue gas analysis is as follows.

$O_2 = 0\%$

$CO_2 = 11\%$

$CO = 2\%$

$N_2 = 87\%$ (by difference)

Figure 4 cannot be used because of the presence of CO.

$$\text{Excess Air} = \frac{0\% - (0.5 \times 2\%)}{0.2682 \times 87\% - [0\% - (0.5 \times 2\%)]} \times 100$$

$$= -4.1\%$$

This means that approximately 4 per cent less than the theoretical air required for complete combustion is being supplied to the burners. If the type of process permits it, the carbon monoxide should be reduced by increasing the combustion air supply.

Occasionally, CO occurs with high $O_2$. This is usually an indication of poor mixing of the fuel and combustion air. Sometimes improvements can be made by adjusting the burner air dampers to create more turbulence where the fuel and air mix. In other instances it may be necessary to replace the burner assembly.

# Heat Losses

## Flue Gas Heat Loss

The largest single source of heat loss in a fuel fired furnace is normally the heat in the flue gas leaving the furnace. The heat loss to the flue gas has two main components. The first is the heat in the dry gas, and the second is the heat in the water vapor leaving the furnace.

The water vapor loss includes the heat required to evaporate the moisture in the flue gas. It is not normally possible to recover the heat of evaporation since this would require lowering the temperature of the flue gas below the point where the moisture will condense. This temperature will be 40°C to 60°C, depending on the fuel and level of excess air. Lowering the flue gas temperature to this extent may be practical if the following requirements are satisfied.

1. There is space for a condensing heat recovery system and there is a use for the recovered heat.
2. The resultant condensed water can be suitably accommodated with respect to corrosion of heat exchanger materials and treatment. Natural gas creates the fewest problems.

The flue gas analysis, in combination with the flue gas temperature, can be used to calculate the flue gas heat loss. The temperature should be taken at the same point as the flue gas analyzer sample. A mercury thermometer can be used if the temperature is less than 300°C, and a thermocouple is suitable for higher temperatures.

Natural gas (Figure 5) and fuel oil (Figure 6) heat losses to the flue gases can be estimated if the excess air and flue gas temperatures are known. This heat loss percentage combines the dry gas and water vapor losses. Detailed calculations of heat losses for any fuel are given in Combustion, Module 5.

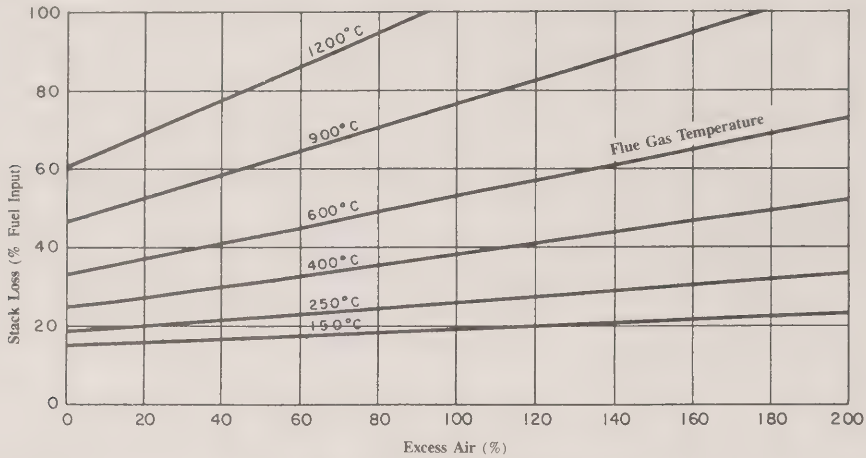
*Example:* A furnace burns natural gas and the excess air is determined to be 77 per cent. The temperature of the gas leaving the furnace is 850°C.

From Figure 5, heat loss = 65%.

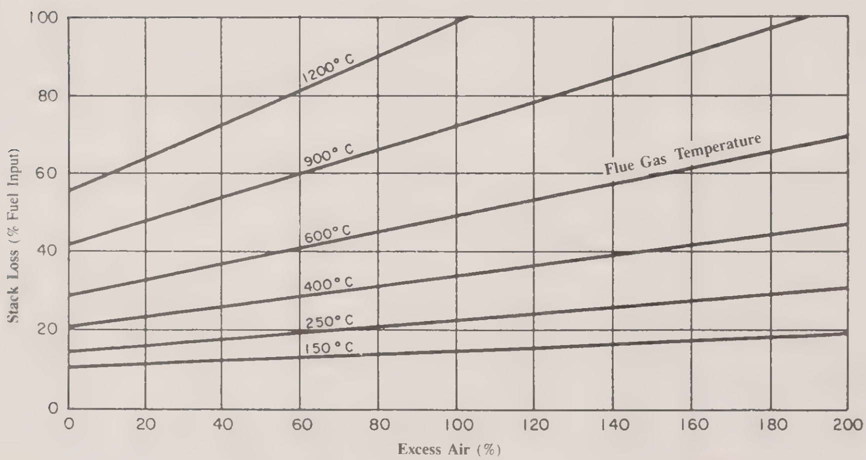
This is the per cent heat loss to the stack. There are additional losses through the furnace walls and roof, which may be as high as 20 per cent of the fuel heat value. As a result, only 15 per cent of the heat input ends up as useful heat to the product. There is good potential for improved energy management in this instance.

Process requirements for some furnaces or dryers require high excess air values which cannot be reduced. Thus, the flue gas heat loss is high, and cannot be reduced by lowering the excess air quantity. It is often possible in these applications to install a heat exchanger to preheat the incoming air with the flue gas leaving the furnace or dryer. The heat loss is then the heat in the flue gas after the heat recovery equipment. Flue gas analysis and temperature should be measured downstream of this equipment.

An example of this is a direct fired malt drying kiln where the temperature of the flue gas is limited to 80°C to avoid damage to the malt. The excess air over that required for complete combustion is several thousand per cent. An Orsat analyzer is not sufficiently accurate in this instance to determine the excess air. Where excess air is more than about 200 per cent, it is necessary to measure either the combustion air or the flue gas quantities directly by using a hot-wire anemometer or Pitot tube. It is sometimes easier to measure combustion air because it is cleaner and cooler. However, any infiltration of air after the measuring point will not be measured, resulting in some inaccuracies.




**Flue Gas Loss - Natural Gas Fuel**
Figure 5




**Flue Gas Loss - No. 2 Oil Fuel**
Figure 6

*Example:* A malt dryer uses natural gas fuel at the rate of 470 $m^3/h$. The exhausted drying air and flue gas mixture is measured as 550 000 kg/h, and the temperature after the heat recovery system is 21°C. Incoming air temperature is 2°C. The heating value of natural gas is 37.2 $MJ/m^3$. The heat loss in the exhausted air and gases can be calculated as follows:

Total heat input = 470 $m^3/h$ x 37.2 $MJ/m^3$

= 17 484 MJ/h

The heat loss (kJ/h) in the exhausted air and gas mixture is calculated by the following equation:

Heat loss, = c x DT x w

where, c = specific heat of the mixture [kJ/(kg·°C)]

DT = Temperature difference between the incoming air and exhausted mixture (°C)

w = Mass flow of mixture (kg/h)

The excess air is very high, so the specific heat of the exhausted air and gas mixture can be taken as the same as for air, which is 1.01 kJ/(kg·°C)

Heat in exhausted mixture above inlet air conditions = 1.01 kJ/(kg·°C) x (21-2)°C x 550 000 kg/h

= 10.55 x $10^6$ kJ/h

= 10 550 MJ/h

$$\text{Percentage of heat input} = \frac{10\,550 \text{ MJ/h}}{17\,484 \text{ MJ/h}} \times 100$$

= 60.3%

There would be some additional heat losses through the exterior surfaces of the equipment. The conclusion is that less than 40 per cent of the heat in the fuel is used for drying the malt despite the installation of heat recovery equipment.

**Radiation and Convection Losses**

The other major heat losses from a furnace are from radiation and convection from the outside surfaces of the furnace enclosure. These losses can be reduced by adding insulation to the outside surfaces, and by ensuring that furnace doors are kept closed.

## Heat Balance

The heat from fuel appears as useful heat to the product plus heat losses to the environment.

Heat input = Useful heat to product + Heat losses

A heat balance is simply a tabulation of all items on both sides of the equation. The total on each side should be identical since energy cannot be created or destroyed. Electric furnace calculations require that the energy input be converted from electrical units to heat units, using the conversion of 1 kWh equalling 3.6 MJ.

The *heat input* is usually taken as the energy in the fuel or electricity supplied to the furnace, but there may be other energy inputs. In a heat treatment furnace, the items being heated may already be above ambient temperature from a previous process and therefore contain heat.

*Example:* A heat treatment furnace heats 1800 kg/h of steel from 40°C to 900°C using natural gas at the rate of 125 $m^3/h$. The heating value of natural gas is 37.2 $MJ/m^3$. Flue gas temperature is 1100°C with 15 per cent excess air.

Total heat input = 125 $m^3/h$ x 37.2 $MJ/m^3$

= 4650 MJ/h

The energy output of the heat balance consists of useful heat to the product, and heat losses.

The *useful heat* is that required to raise the temperature of the steel to 900°C. From Table 4, the specific heat of steel is 0.5 kJ/(kg·°C). Useful heat is mass times specific heat times temperature rise.

$$\text{Useful heat} = \frac{1800\ \text{kg/h} \times 0.5\ \text{kJ/(kg·°C)} \times (900 - 40)\ °\text{C}}{1000\ \text{kJ/MJ}}$$

$$= 774\ \text{MJ/h}$$

$$\text{Per cent useful heat} = \frac{774}{4650} \times 100$$

$$= 16.6\%$$

Some fuel value may be derived from the product itself. In a carbon electrode baking furnace, appreciable quantities of hydrocarbon vapors are generated from the pitch used as a binder. The vapors are partially burned within the furnace producing useful heat.

*Heat losses* are the sum of flue gas, radiation, and convection losses. Flue gas heat loss is the major source of lost energy. Radiation and convection losses from the furnace enclosure are difficult to measure accurately. The radiation and convection losses are normally calculated as the difference between the total heat input and the sum of the useful heat to the product and the flue gas loss.

The flue gas loss at 1100°C and 15 per cent excess air can be read from Figure 5 as 62 per cent of fuel input.

$$\text{Total flue gas heat loss} = 4650\ \text{MJ/h} \times \frac{62}{100}$$

$$= 2883\ \text{MJ/h}$$

$$\text{Radiation and convection losses} = 4650 - (774 + 2883)$$

$$= 993\ \text{MJ/h}$$

$$\text{Per cent radiation and convection losses} = \frac{993}{4650} \times 100$$

$$= 21.4\%$$

It is now possible to make a *heat balance* for the furnace.

| Heat Input | | Heat Output | | |
|---|---|---|---|---|
| Natural Gas | 4650 MJ/h | Useful heat to product | 774 MJ/h | 16.6% |
| | | Flue gas loss | 2883 | 62.0 |
| | | Radiation and convection losses | 993 | 21.4 |
| Totals | 4650 MJ/h | | 4650 MJ/h | 100% |

The conclusion is that the greatest heat loss is in the flue gas. The per cent excess air at 15 per cent is quite low. It may be possible to recover some of the heat in the flue gas by installing heat recovery equipment.

# Heat Transfer

The transfer of heat from the burner flame to the product can be by conduction, convection, or radiation, and in most instances a combination of all three.

### Conduction

Heat transfer to the product by conduction is only significant in indirect heated equipment, where the product is isolated from the flame by a heat exchange surface. Muffle furnaces and furnaces using radiant tube heaters (Figures 7 and 8) are examples of indirect heating arrangements. Heat conducted through a solid can be calculated.

$$Q = \frac{k \times A \times DT \times 3.6}{t}$$

where, $Q$ = Heat conducted (kJ/h)

$k$ = Thermal conductivity of solid [W/(m$^2\cdot$°C)]

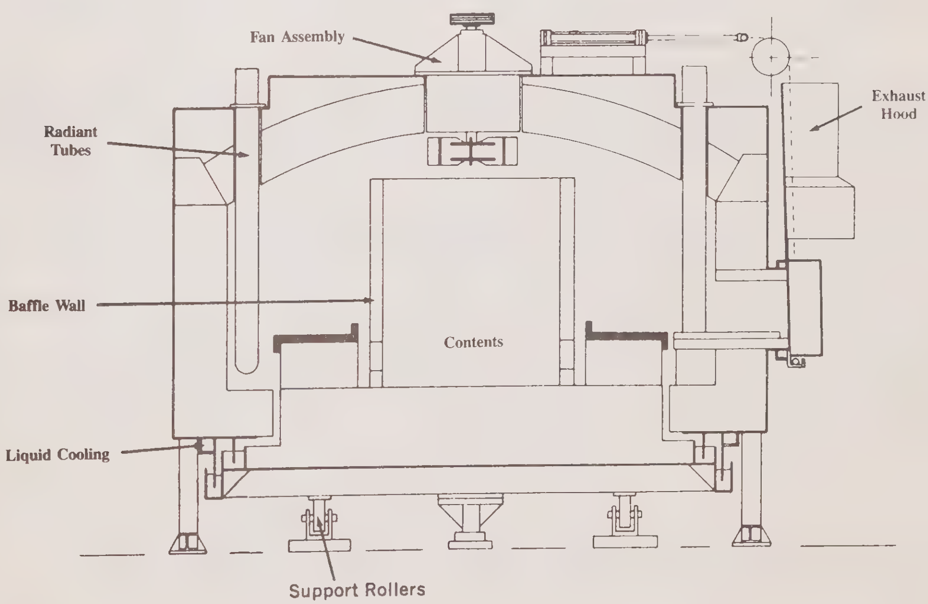
$A$ = Surface area (m$^2$)

$DT$ = Mean temperature differential across solid (°C)

$t$ = Thickness of solid (m)

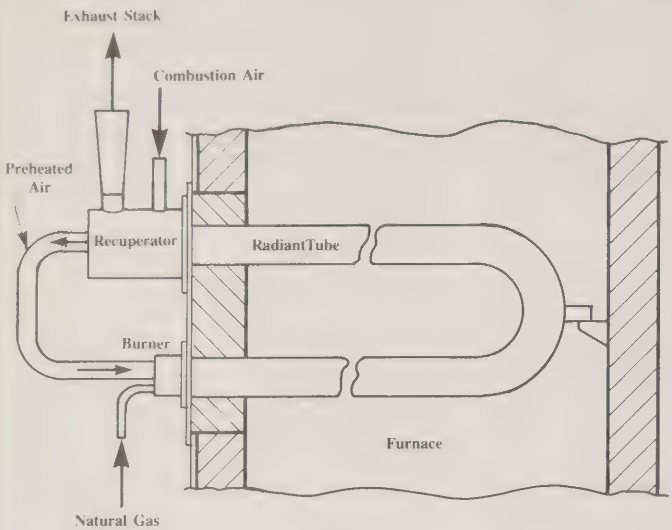
3.6 = Conversion factor from watts to kilojoules per hour

Typical $K_1$ values for different materials are given in Table 2. The foregoing equation shows that rate of heat transfer increases in proportion to surface area, and to temperature differential across the heater, and is inversely proportional to material thickness.

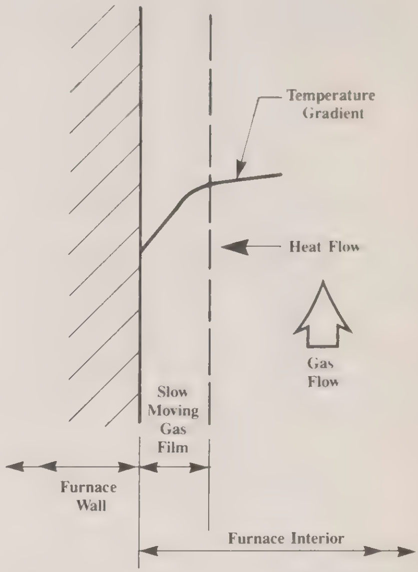



**Radiant Tube Gas-Fired Rotary Furnace**
Figure 7

Courtesy of CAN-ENG




**Bolt-On Recuperator For Heat-Treat Furnace**
Figure 8




**Heat Flow By Convection**
Figure 9

*Example:* A muffle furnace has a 10 mm thick, high nickel steel enclosure with a surface area of 55 $m^2$. Useful heat to the product, all of which is transmitted through the wall, is 1.9 GJ/h. From Table 2, thermal conductivity of high nickel steel is 31 W/(m·°C). The temperature drop through the muffle wall can be determined as follows:

$$\text{Heat conducted} = \frac{31\ \text{W/(m·°C)} \times 55\ \text{m}^2 \times \text{DT} \times 3.6}{0.01\ \text{m}}\ \text{kJ/h}$$

Heat conducted is 1.9 GJ/h, or $1.9 \times 10^6$ kJ/h

Rearranging the equation,

$$\text{DT} = \frac{1.9 \times 10^6 \times 0.01}{31 \times 55 \times 3.6}$$

$$= 3.1\ °\text{C}$$

The temperature drop across the enclosure is 3.1°C at the specified rate of heat transfer.

## Convection

Heat transfer by convection takes place at the boundary between a solid wall and a gas or liquid. Intermingling takes place between the stagnant layer of fluid at the wall and the moving fluid stream next to the stagnant layer (Figure 9). This means of heat transfer is most important in furnaces operating at relatively low temperatures, below

600°C. Tests on rate of heat transfer by convection show that the rate is proportional to surface area and temperature differential between the solid and the fluid. It also increases as the velocity of the fluid over the wall surface increases, but not proportionally. The following approximate equation can be used for gases:

$$Q = 23.46 \times A \times DT \times V^{0.78} \times d$$

where, Q = Rate of convection heat transfer (kJ/h)

A = Area of heat transfer ($m^2$)

DT = Temperature differential between solid and fluid (°C)

V = Fluid velocity (m/s)

d = Gas density ($kg/m^3$)

*Example:* A furnace has dimensions of 3 metres long by 1 metre x 1 metre cross section. Flue gas flows through the furnace at an average velocity of 0.5 m/s with a gas temperature of 500°C. Temperature differential between furnace walls and flue gas averages 150°C. For most practical purposes, the density of air can be used for flue gas. From standard references, density of air at 500°C is 0.458 $kg/m^3$. The average rate of heat transfer by convection to the walls, floor and roof can be determined as follows.

Furnace area swept by flue gas = (1 + 1 + 1 + 1)m x 3m

= 12 $m^2$

$$Q = 23.46 \times 12m^2 \times 150°C \times (0.5m/s)^{0.78} \times 0.458kg/m^3$$

$$= 11\ 263\ kJ/h$$

**Radiation**

Heat transfer by radiation becomes significant for furnace temperatures above 600°C. Any hot body emits radiation in the form of heat, which can be received by another solid body in the path of heat radiation. In an electric furnace the walls, which are heated by the electrodes, emit heat radiation to the furnace contents. The furnace contents in turn radiate heat back to the walls.

The amount of heat radiated from a solid body is proportional to the fourth power of its absolute temperature, and directly proportional to its emissivity. Absolute temperature is the number of degrees above absolute zero and is measured in degrees Kelvin (K). Degrees Kelvin equals degrees Celsius plus 273°.

Emissivity is a measure of the heat radiated from an object compared to that radiated from a similar sized "black body" at the same temperature. The maximum value of emissivity is that of the "black body", which is 1. Typical emissivity values for furnace walls and oxidized steel are 0.8 to 0.9. Because both the hot body, (the furnace wall) and the cooler body, (the furnace contents) are emitting radiation, the net total heat received by the contents is the difference between the heat emissions of the two bodies. The equation for a furnace is:

$$Q = K \times F \times \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

where, Q = Rate of radiation heat transfer (kJ/h)

K = "Black body" coefficient (20.6)

F = Overall radiation factor depending on emissivity and surface areas of the furnace walls and contents

$T_1$, $T_2$ = Absolute temperatures of hot and colder bodies respectively (K)

$$F = \frac{A_1}{\frac{1}{e_1} + \left(\frac{A_1}{A_2}\right)\left(\frac{1}{e_2} - 1\right)}$$

where, $A_1$ = Surface area of furnace contents exposed to walls ($m^2$)

$A_2$ = Surface area of furnace walls ($m^2$)

$e_1$ = Emissivity of furnace contents

$e_2$ = Emissivity of furnace walls

Values of emissivities are provided in Table 3

*Example:* A furnace with a square cross section of 1 metre by 1 metre is heating carbon steel billets 100mm by 100mm. Furnace wall temperature is 1000°C. The furnace floor does not radiate heat. From Table 3, emissivity of a fireclay brick furnace wall is 0.75, and emissivity of oxidized carbon steel is 0.80. The heat input to the billet per metre of length when the steel is heated to 650°C can be calculated.

$$A_1 = (0.1 + 0.1 + 0.1) \times 1$$

$$= 0.3 \text{ m}^2$$

$$A_2 = (1 + 1 + 1) \times 1$$

$$= 3 \text{ m}^2.$$

$$F = \frac{0.3}{\frac{1}{0.8} + \left(\frac{0.3}{3}\right)\left(\frac{1}{0.75} - 1\right)}$$

$$= 0.234$$

$$T_1 = 1000°\text{C} + 273°$$

$$= 1273\text{K}$$

$$T_2 = 650°\text{C} + 273°$$

$$= 923\text{K}$$

$$\text{Heat radiated/metre length} = 20.6 \times 0.234 \times \left[\left(\frac{1273}{100}\right)^4 - \left(\frac{923}{100}\right)^4\right]$$

$$= 91\ 604 \text{ kJ/h}$$

Radiation also takes place from hot gases to the furnace contents. This method of heat transfer does not follow the same laws as the radiation from solid bodies. Radiation from a luminous flame is higher than from a clear flame or hot gases.

# Heat Recovery

## Heat Exchangers

Since most of the heat losses from a fuel fired furnace appear as heat in the flue gas, the recovery of this heat can result in substantial energy savings. A common method is to install a heat exchanger at the furnace exit. A heat exchanger can be used to transfer heat from the hot flue gas to the incoming combustion air, or to heat water used elsewhere in the plant. The rate of heat transfer is proportional to the surface area of the heat exchanger, and to the mean temperature differential between the flue gas and the combustion air.

$$Q = k \times A \times LMTD \times 3.6$$

where, Q = Rate of heat transfer (kJ/h)

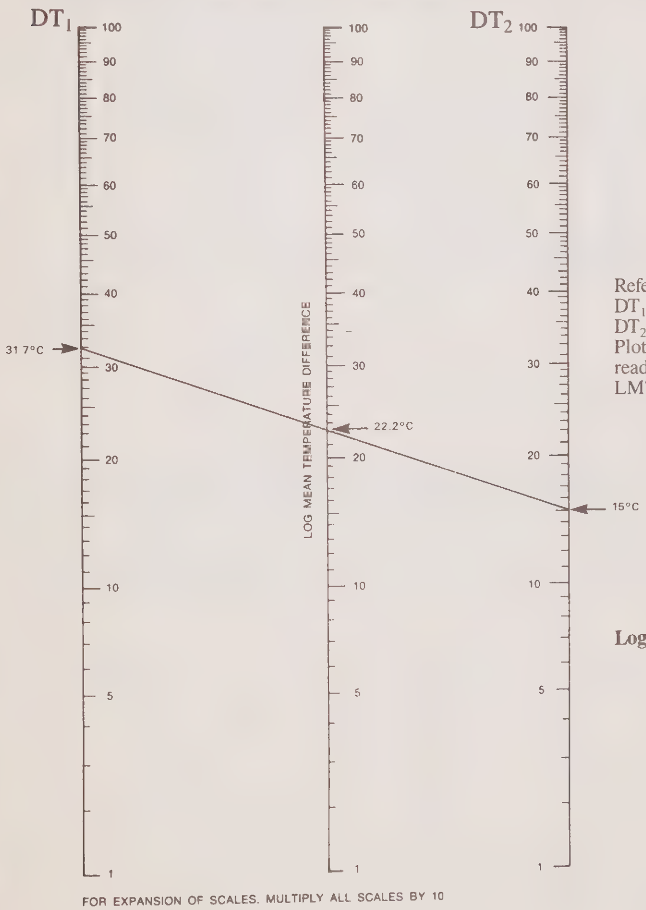
k = Heat transfer coefficient of heat exchanger [W/(m$^2$·°C)]

A = Surface area of heat exchanger (m$^2$)

LMTD = Logarithmic mean temperature difference (°C)

3.6 = Conversion factor from watts to kilojoules per hour

Logarithmic mean temperature difference (LMTD) can be calculated or read from Figure 10.




Refer to example numbers on page 19.
$DT_1$ = 31.7°C
$DT_2$ = 15°C
Plot as shown and draw a connecting line. LMTD can be read where the line crosses middle scale.
LMTD = 22.2°C.

**Logarithmic Mean Temperature Difference Chart for Heating or Cooling Applications**
Figure 10

$$\mathrm{LMTD} = \frac{DT_1 - DT_2}{\ln\left(\frac{DT_1}{DT_2}\right)}$$

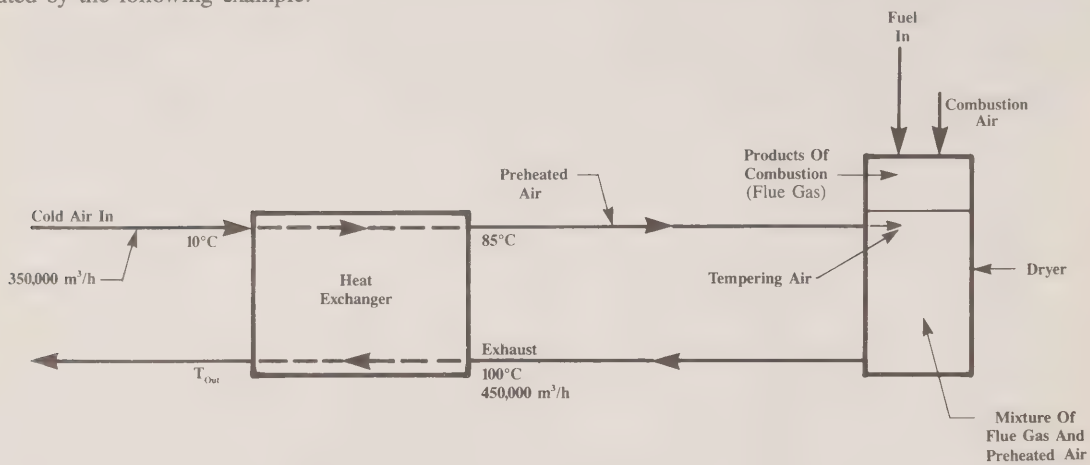
Where, LMTD = Log mean temperature difference (°C)

$DT_1$ = Greater temperature difference between the flue gas and the heated air or water (°C)

$DT_2$ = Lesser temperature difference between the flue gas and the heated air or water (°C)

"ln" is the natural logarithm

A heat exchanger may be used to heat water with the heat from flue gases. An important design consideration is how close the heated water temperature should be to the temperature of the hot gas entering the exchanger. It is not possible to heat the fluid to a temperature above the temperature of the hot gas entering, regardless of the relative fluid and hot gas flows. Small temperature differentials imply large heat exchanger surfaces. This is illustrated by the following example.




**Tempering Air Heat Exchanger**
Figure 11

*Example:* A heat exchanger is to be added to a dryer which is exhausting 450 000 m³/h of moist air at 100°C. The exhausted air is used to heat up 350 000 m³/h of incoming air from an ambient temperature of 10°C to 85°C, which is within 15°C of the hot exhausted air (Figure 11). The heat exchanger design has a heat transfer coefficient quoted by the manufacturer of 28 W/(m²·°C). Heat given up by the exhausted air is equal to the heat gained by the incoming air, since there are no significant heat losses in a heat exchanger of this type. Density of air at standard conditions is 1.204 kg/m³, and specific heat is 1.006 kJ/(kg·°C). The surface area of the heat exchanger required can be calculated as follows:

Cold air heat gain (Q) = Volumetric flow x Density x Specific heat x Temperature rise

$= 350\ 000\ \mathrm{m^3/h} \times 1.204\ \mathrm{kg/m^3} \times 1.006\ \mathrm{kJ(kg{\cdot}°C)} \times (85\text{-}10)°\mathrm{C}.$

$= 31.79 \times 10^6\ \mathrm{kJ/h}$

Exhaust air heat loss = Volumetric flow x Density x Specific heat x Temperature drop

$= 450\ 000 \times 1.204 \times 1.006 \times (100°\mathrm{C} - T_{out})\ \mathrm{kJ/h}$

Cold air heat gain = Exhaust air heat loss

This can be expressed as

$$31.79 \times 10^6 = 450\,000 \times 1.204 \times 1.006 \times (100°C - T_{out})\ kJ/h$$

Rearranging the equation:

$$(100°C - T_{out}) = \frac{31.79 \times 10^6}{450\,000 \times 1.204 \times 1.006}$$

$$= 58.3°C$$

Heat exchanger exhaust temperature, $T_{out} = 100°C - 58.3°C = 41.7°C$

Maximum temperature differential, $DT_1 = 41.7°C - 10°C$

$$= 31.7°C$$

Minimum temperature differential, $DT_2 = 100°C - 85°C = 15°C$

The logarithmic mean temperature difference is

$$LMTD = \frac{31.7°C - 15°C}{\ln\left(\frac{31.7°C}{15°C}\right)}$$

$$= 22.3°C$$

Cold air heat gain (Q) = $31.79 \times 10^6$ kJ/h = 28 W/(m$^2$·°C) x A x 22.3°C x 3.6 kJ/h

$$\text{Surface area, } A = \frac{31.79 \times 10^6}{28 \times 22.3 \times 3.6}$$

$$= 14\,142\ m^2$$

If the cold air is heated to within 5°C of the exhausted moist air instead of 15°C, the size of the heat exchanger required is increased considerably. The calculations are as follows:

Temperature of heated air = 100°C − 5°C

= 95°C

Cold air heat gain = 350 000 m$^3$/h x 1.204 kg/m$^3$ x 1.006 kJ/(kg·°C) x (95 − 10)°C

= $36.03 \times 10^6$ kJ/h

$$(100°C - T_{out}) = \frac{36.03 \times 10^6}{450\,000 \times 1.204 \times 1.006}$$

$$= 66.1°C$$

$$T_{out} = 100°C - 66.1°C$$
$$= 33.9°C$$
$$DT_1 = 33.9°C - 10°C$$
$$= 23.9\ °C$$
$$DT_2 = 100\ °C - 95°C$$
$$= 5°C$$
$$LMTD = \frac{23.9°C - 5°C}{\ln\left(\frac{23.9°C}{5°C}\right)}$$
$$= 12.1°C$$
$$\text{Surface Area (A)} = \frac{36.03 \times 10^6}{28 \times 12.1 \times 3.6}$$
$$= 29\ 541\ m^2$$

It should be noted that the reduction in the temperature differential to 5°C would require the heat exchanger area to be slightly more than doubled. An increase in design temperature rise of the incoming air from (85°C − 10°C) = 75°C to (95°C − 10°C) = 85°C results in an increase in heat recovery of

$$\frac{(85°C - 75°C)}{75°C} \times 100 = 13\ \%$$

A careful analysis of capital costs and savings in fuel costs for different possible heat exchanger sizes is important.

**Recuperators**

Heat exchangers, which transfer heat from hot flue gas to combustion air, are sometimes called recuperators. The hot gas passes inside tubes arranged in bundles. The combustion air is directed over the outside of the tubes by means of a series of baffle plates.

Another form of gas to air heat exchanger is a regenerative air heater which has two separate sets of refractory bricks. These are alternately heated by the hot flue gas and cooled by the incoming combustion air. At regular intervals dampers automatically divert the hot gas and cold air from one set of bricks to the other. Thus, one set of bricks is being heated by the hot gas while the other set is heating the combustion air. The advantage of the regenerative air heater is that very high temperature gas can be handled without the need for expensive thin wall tubing made from stainless steel or other heat resistant materials.

**Economizers**

Economizers are heat exchangers which use hot flue gas to heat water. Economizers can be considered where hot water is required whenever the furnace is operating. If the use of hot water and the operation of the furnace does not always occur simultaneously, it may be practical to install an insulated hot water storage tank. This would level out the effect of variations in the hot water supply and demand.

The heated water passes inside metal tubes arranged in bundles. The hot flue gas passes over the outside of the tubes, which are usually finned to assist in the transfer of heat from the gas to the water. The tube metal temperature is close to that of the water temperature. Economizers can therefore extract heat from very high temperature gas without the use of expensive alloy steel tube material. It is important to ensure that the water flow is always high enough to avoid boiling of the water inside the tubes. If this happens, the tubes will overheat and may fail.

There is a counterflow arrangement in the economizer so that the gas leaving the economizer will be cooled to the lowest possible temperature by the cold water entering the economizer. This provides the most effective use of the flue gas heat.

### Waste Heat Boilers

Waste heat boilers use hot flue gas heat to produce steam. In most instances there is a common steam header into which the waste heat and fuel fired boilers are connected. The fuel fired boilers will then supply the difference between the steam demand and the steam supplied by the waste heat boiler.

Economizers are often used with waste heat boilers to preheat the feedwater to the boiler. The hot flue gas passes through the boiler before going to the economizer.

## Product Temperature Control

Control of product temperature is important in heat treating furnaces and similar applications. High temperatures may cause oxidizing or burning of the furnace contents, while low temperatures result in improper hardening or annealing. Location of the point of temperature measurement is important. The measuring element should not be exposed to radiation from the flame, nor should it be close to the furnace wall. Usually, the rate of energy input is varied in order to maintain a suitable furnace gas temperature. In large furnaces it is important to maintain an even temperature across the furnace. Continuous furnaces may require multiple heating zones each with banks of burners and a temperature controller. The ratio of fuel to combustion air should be monitored carefully to keep the excess air as low as is practical.

## Safety

Safety implications must be evaluated when implementing energy management opportunities. The addition of a heat exchanger to recover flue gas heat by preheating combustion air, means that the air ducting to the burner may be at 400°C. The maximum temperature to which operating staff should be exposed is 50°C. Thus, protection for the operating personnel should be provided by insulating the air ducting. The protective insulation will also effect some heat savings, so it is worthwhile to consider insulating all hot ducting.

## Energy Management Potential

One of the first steps to be taken in a program of improved energy management is to become aware of the potential savings. It is helpful to compare the actual energy input with the energy usefully applied to the product.

Oil or gas energy input can be read directly if there is a meter which measures the fuel consumed by specific equipment. If a meter is not installed, arrangements for a temporary positive displacement type meter should be made. Care should be taken to choose a meter which provides sufficient accuracy for this purpose. It should be possible to measure within one per cent of the fuel use.

Energy input to an electric furnace should be measured by a wattmeter, which requires a measurement of voltage and current in two phases of a three phase power supply. If heating is provided by a resistance element and the voltage does not fluctuate it is possible to use a clamp-on ammeter to give an instantaneous indication of the energy input.

*Example:* A resistance type electric furnace operating on 550 volts, 3 phase power supply has an average current per phase of 200 amps. If the phases are reasonably balanced the electrical power input can be calculated from the equation

$$\text{Power Input} = \frac{1.732 \text{ x Volts x Amps x Power Factor}}{1000\text{W/kW}} \text{ kW}$$

Since it is a resistive load the power factor is 1.0

$$\text{Power input} = \frac{1.732 \text{ x } 550 \text{ x } 200 \text{ x } 1.0}{1000}$$

$$= 190.5 \text{ kW}$$

Using the conversion one kW equals 3.6 MJ/h.

$$\text{Heat energy input is} = 190.5 \times 3.6 = 685.8\text{MJ/h}$$

Electrical demand charges must be considered for electric furnaces. Users of large amounts of electricity pay for the peak load, measured in kilowatts, for each month as well as the electrical energy used, measured in kilowatt-hours. In some electric supply contracts the highest peak load measured in the previous 12 months is used to calculate the demand charge. The demand charges can be reduced by automatically shutting down nonessential electrical loads whenever a new peak in electrical load is approached. It may also be possible to reduce load on some furnaces to reduce the peak demand. Substantial savings in electricity costs can be achieved with the use of a "peak-load" control system.

Calculation of the energy usefully applied to the product requires that the weight of product processed per unit of time be known. If the furnace is heating or melting metals, the specific heat and heat required for melting must be known. Typical values are given in Table 4.

*Example:* A furnace is melting aluminum at the rate of 4000 kg/h. From Table 4, heat of melting is 1095 kJ/kg. The heat usefully applied to the product can be determined.

$$\begin{aligned}\text{Heat to product} &= 4000 \text{ kg/h} \times 1095 \text{ kJ/kg}\\ &= 4.38 \times 10^6 \text{ kJ/h}\\ &= 4380 \text{ MJ/h}\end{aligned}$$

Calculation of energy applied to evaporate water or solvents requires a knowledge of the initial and final dryness and amount evaporated. Typical values of heat of vaporization are given in Table 5. It should be noted that some solvents are combustible and provide energy input to the dryer.

*Example:* A kiln is drying wood from 60 to 20 per cent moisture. The drying of each 3 tonne batch takes 10 hours. The useful heat applied to the product can be determined as follows:

$$\begin{aligned}\text{Batch moisture} &= 3 \text{ tonnes} \times \frac{60}{100}\\ &= 1.8 \text{ tonnes of water}\end{aligned}$$

$$\begin{aligned}\text{Oven dry wood} &= 3 \text{ tonnes} - 1.8 \text{ tonnes}\\ &= 1.2 \text{ tonnes}\end{aligned}$$

The final product contains 1.2 tonnes of oven dry wood, and consists of 20 per cent moisture plus 80 per cent oven dry wood.

$$\begin{aligned}\text{Total weight of 20 per cent moisture wood} &= \frac{1.2}{0.8} \text{ tonnes}\\ &= 1.5 \text{ tonnes}\end{aligned}$$

$$\begin{aligned}\text{Moisture in final product} &= 1.5 - 1.2 \text{ tonnes}\\ &= 0.3 \text{ tonnes}\end{aligned}$$

$$\begin{aligned}\text{Total amount of moisture evaporated} &= 1.8 - 0.3 \text{ tonnes}\\ &= 1.5 \text{ tonnes}\end{aligned}$$

From Table 5 heat of evaporation of water is 2450 kJ/kg

Heat to evaporate product moisture $= 1.5 \text{ t} \times 1000 \text{ kg/t} \times 2450 \text{ kJ/kg}$

$= 3.675 \times 10^6 \text{ kJ}$

or 3.675 GJ

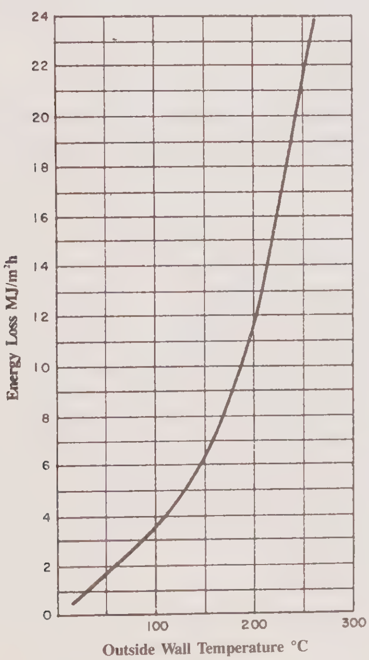
Average heat input over 10 hours $= \dfrac{3.675}{10}$

$= 0.3675 \text{ GJ/h}$

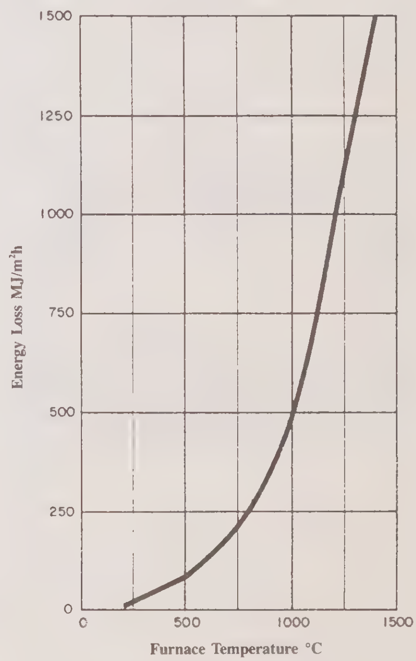
or 367.5 MJ/h

Calculation of heat losses from flue gas was covered in the section on the combustion process. This is the major loss in a fuel-fired furnace. In an electric furnace, heat loss through the furnace walls and ducts is the most significant item. Heat loss through the furnace enclosure can be calculated by difference, but it is useful to estimate the amount directly so that the potential savings of adding insulation can be determined.

Heat loss from the furnace enclosure increases as the temperature of the outside surface in contact with the atmosphere increases. Figure 12 is a curve of heat loss per square metre versus surface temperature. The curve applies where the furnace is installed indoors at normal ambient temperatures.




**Energy Loss From Furnace Walls Versus Outside Wall Temperature**
Figure 12




**Energy Loss By Radiation Through Openings Versus Furnace Temperature**
Figure 13

Openings in the furnace enclosure are a substantial source of heat loss. The heat loss through openings by radiation can be estimated (Figure 13). The curve does not include losses caused by air leaking in or gas leaking out. The most effective way to minimize these losses is to control furnace pressure.

*Example:* A furnace has an opening 2 metres long by 150 mm high, and is operating at 1200°C. From Figure 13, heat radiated is 910 MJ/(m$^2$.h). The heat radiated through the opening can be calculated as follows:

$$\text{Heat radiated from opening} = 2 \text{ m} \times 0.15 \text{ m} \times 910 \text{ MJ/(m}^2\cdot\text{h)}$$

$$= 273 \text{ MJ/h}$$

The furnace operates 2000 hours per year, and fuel costs \$5/GJ.

$$\text{Annual heat loss cost} = \frac{273 \text{ MJ/h} \times 2000 \text{ h/yr} \times \$5/\text{GJ}}{1000 \text{ MJ/GJ}}$$

$$= \$2{,}730$$

## Energy Audits

Many Energy Management Opportunities in the operation of furnaces, dryers, and kilns can be recognized by performing a walk through audit. It is often helpful to engage someone for this task who is not normally associated with the plant operation. A fresh viewpoint will often pick up items which have been overlooked in the past. Typical energy wasting items which can be identified in this manner are open or missing furnace doors, deteriorating insulation, and under-loaded or over-loaded equipment.

Some energy wasting items which can be identified during a walk through audit are more difficult to analyze than those just described. It may have been observed, for instance, that the temperature of the flue gas leaving a furnace is very high at 500°C. The economics of recovering this energy are not immediately obvious and must be thoroughly investigated. A number of key questions must be answered.

- What quantity of energy is available in the gas stream?
- Can this energy be used?
- What is the capital cost for the equipment needed to recover the energy?
- What are the energy savings and will the resulting cost reductions pay for the equipment needed?

A diagnostic audit will answer the above questions and lead to a determination of the financial feasibility of the Energy Management Opportunity.

# EQUIPMENT SYSTEMS

## Furnaces

The purpose of a process furnace is to apply heat to the contents in a controlled manner. The furnace may be used for heating metals to a precisely controlled temperature for heat treatment, or for melting. Furnaces are manufactured in many different types and sizes, some of which are described in this section.

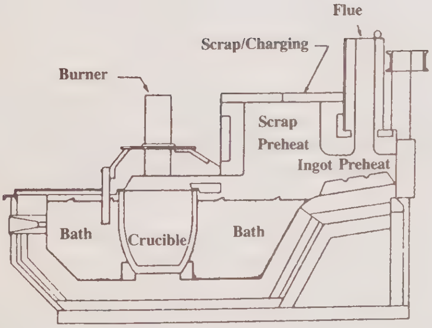
Furnaces may be batch or continuous type. Furnaces, which generate heat by burning fuel, may be of the direct or indirect fired types. Furnaces are also heated from electric resistance heaters.

### Batch Furnaces

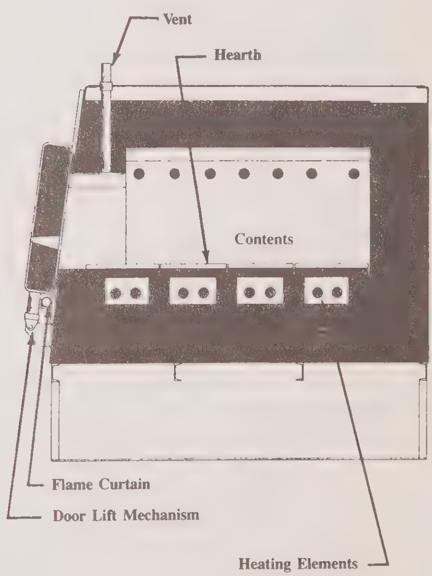
Batch furnaces process the product in batches, which means that the furnace doors must be opened and closed at the beginning and end of the batch cycle. Since this is a significant source of energy loss, the loading and unloading times should be minimized. It is also important to load the furnace completely to minimize the energy loss per unit of product. Examples of this type of furnace are shown in Figures 14 and 15.

Figure 14 shows a crucible melting furnace used for nonferrous metals. Metal scrap is loaded into the furnace in batches, and the molten metal tapped off as required.

Figure 15 shows a high temperature electric furnace used for the heat treatment of steel.




**Crucible Type Melting Furnace**
Figure 14

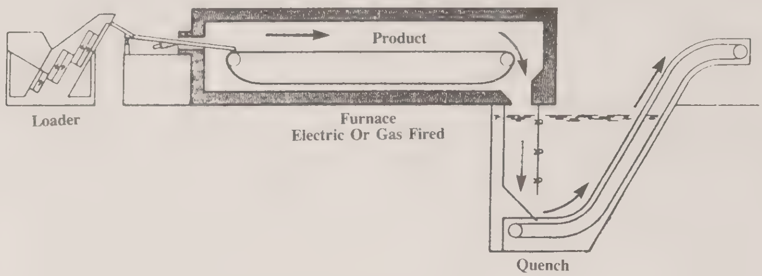



**High Temperature Electric Box Furnace**
Figure 15

Courtesy of CAN-ENG

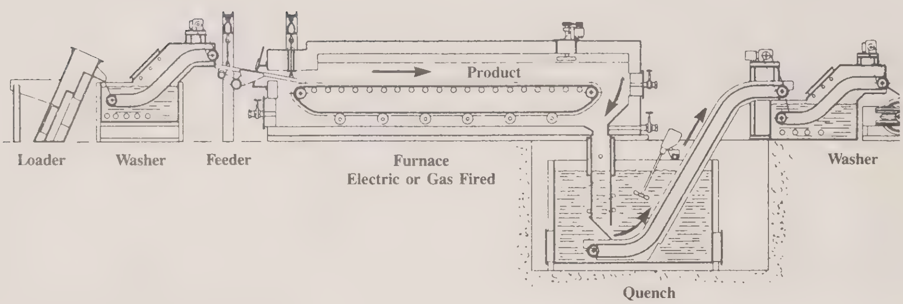
## Continuous Furnaces

Continuous furnaces process the product continually by moving it through the heating zones on chain or conveyor. Since the loading and unloading doors are open all or part of the operating time, there is a significant heat loss through these openings. Continuous furnaces also may have a significant heat loss because of the conveying mechanism, which is heated to the operating temperature with the product. If the conveyor cools off outside the furnace before reentering the loading area, the energy required to heat the conveyor is not used productively. Thus, it is better if the conveyor stays within the heated furnace area. Examples of this type of furnace are shown in Figures 16 and 17.




**Atmosphere Conveyor Belt Furnace**
Figure 16

Courtesy of CAN-ENG




**Continuous Hardening and Quench Belt Furnace**
Figure 17

Courtesy of CAN-ENG

## Direct Fired Furnaces

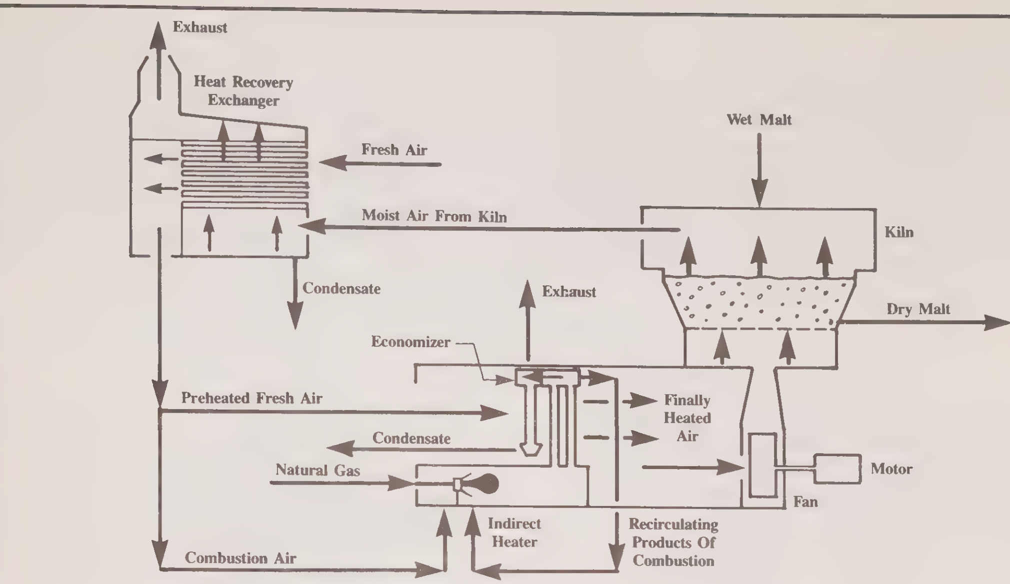
The products of combustion are in direct contact with the product being heated in a direct fired furnace. The heat transfer process from the flame to the product is more effective than with an indirect heated furnace, where the flue gas is not in direct contact with the product. The higher rate of heat transfer which can be achieved with direct fired furnaces can lead to local surface overheating of the product, unless the furnace temperature is properly controlled.

## Indirect Heated Furnaces

In indirect heated furnaces the products of combustion are not in direct contact with the product being heated (Figure 7). Heat is transferred through some form of heat exchanger.

This type of furnace may be used to provide a controlled environment for oxidizing or reducing, by introducing an artificial atmosphere independent of the combustion process. Since the heat transfer from the flame to the product is not as effective as the direct fired furnace, it can be expected that the flue gas temperature will be higher, resulting in higher heat losses unless heat recovery is used.

There are a few special considerations for indirect fired furnaces which affect the heat balance calculations. If a controlled atmosphere is maintained inside the furnace, the heat input and output of the gas entering and leaving the furnace must be included in the heat balance. If heat is required for the preparation of the atmosphere, the energy required in the gas generator must be included as part of the total heat input to the furnace. Electrical energy used for refrigeration or other purposes in the gas generator must also be included.




**Malt Dryer**
Figure 18

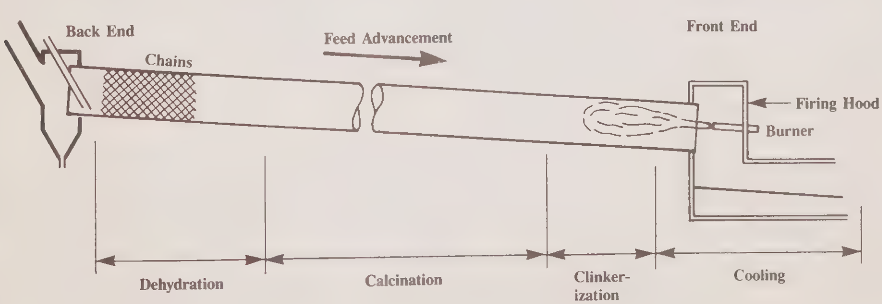
# Dryers

Dryers use heat to evaporate water or solvents from materials such as lumber, grain, ceramics, paint, and carbon electrodes. The same principles of energy management described for furnaces also apply to dryers, and much of the equipment is similar in concept. A major difference is in the operating temperature, which is generally much lower than furnaces, to avoid damage to the product. As a result, direct fired heaters must operate with very high percentages of excess air. This means that excess air cannot be reduced to achieve energy savings. Indirect fired dryers can be operated at normal values of excess air within the combustion chamber. With direct and indirect fired heaters there is a large amount of heat in the exhausted air in the form of evaporated water or solvent. Often the solvent must be incinerated before discharge to the atmosphere by burning additional fuel in the dryer discharge, and raising the temperature to about 900°C. Recovery of the heat in the dryer exhaust can be achieved by a heat exchanger which is used to preheat the incoming air for drying with indirect fired dryers or the combustion air for firing in direct dryers. An indirect malt drying system used in the brewing industry is shown in Figure 18.

# Kilns

There is no fundamental difference between furnaces and kilns from an energy management viewpoint. The ceramic and brick industries use stationary kilns. Rotary kilns are used by the cement, and pulp and paper industries (Figure 19).

Some rotary kilns burn pulverized coal or refuse derived fuel (R.D.F.). The large heat input to rotary kilns provides opportunities for the installation of heat exchangers to recover flue gas heat.

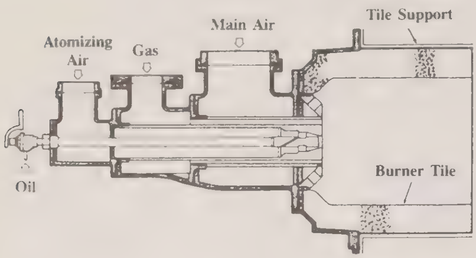



**Rotary Kiln**
Figure 19

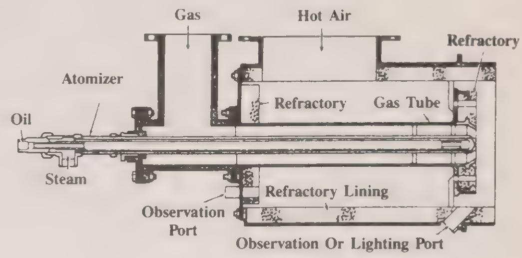
# Burners

Burners are designed to mix the fuel and combustion air thoroughly, and, in the case of liquid fuels, to atomize the fuel for ignition. Thorough mixing of the fuel and air is achieved by creating turbulence at the burner outlet. This requires a pressure drop between the air supply duct to the burner and the burner outlet to the furnace. The pressure drop is created by nozzles or dampers within the burner assembly. The burner is also designed to create the flame shape that is required by the furnace. Typical burners are shown in Figures 20 and 21.

Burners may be designed to burn one or more types of fuel either singly or in combination. Combination fuel firing can be useful where a waste fuel is available, but not in sufficient quantity to satisfy the total heat energy requirements.




**Combination Heavy Oil Or Gas Burner**
Figure 20




**Combination Burner For Use with Air Preheated Up To 600°C**
Figure 21

Courtesy of North America Mfg. (Canada) Inc.

# Burner Controls

A properly set up system is the key to efficient burning of the fuel, by maintaining the minimum amount of excess air without significant combustibles in the flue gas for all firing rates.

Proper control of the ratio of fuel to air in fuel fired furnaces minimizes the flue gas loss. The basic method of achieving this is to operate the fuel control valve and the combustion air dampers from a common controller. The relative positions of the fuel valve and the air dampers can be altered by an adjustable cam or link, if the control linkage is mechanical. If the control system is pneumatic or electronic, the ratio of fuel flow to air flow can be adjusted remotely from the furnace control panel.

Variations in furnace output, fuel pressure, fan performance, or other conditions may result in undesirable variations in the fuel/air ratio with the described basic control system. A more accurate method of control includes metering the actual fuel and air flows to the burners, and using these measurements to readjust the air flow to automatically maintain the desired fuel/air ratio.

A further refinement uses a continuous measurement of the oxygen content of the flue gas. The air flow control is readjusted automatically to maintain a fixed level of oxygen in the flue gas. A constant percentage of excess air to the burners will be achieved by this means. In some circumstances it may be advantageous to also measure the combustibles content of the flue gases and maintain combustibles at a very low level of say 100 to 200 mg/kg.

Control systems today are usually electronic instead of the older pneumatic or mechanical systems. However, technology is changing rapidly in this field and microprocessor based systems will soon be used on furnaces.

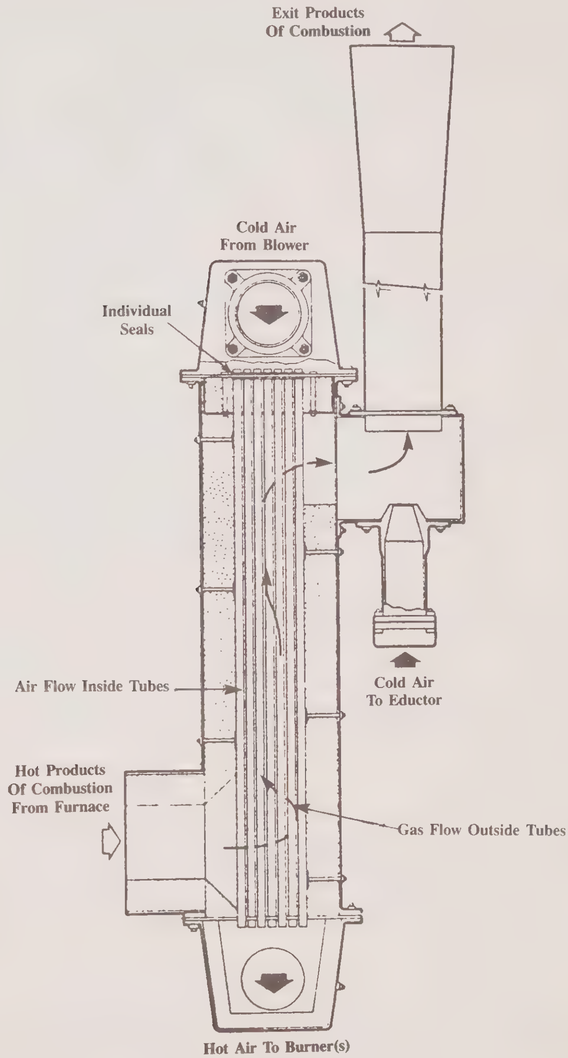
# Insulation

Insulation is used to retain heat within the furnace enclosure. A significant development in this field has been the use of ceramic fiber insulation, which is a better insulator than solid refractory material and also requires less heat to reach the operating temperature. The disadvantages are higher initial cost and low resistance to physical damage. A layer of refractory on the bottom of the furnace and other areas subject to damage is normally used to protect the ceramic fiber. Further layers of ceramic fibre insulation can be installed on the outside of the refractory as required.

# Heat Recovery

Substantial amounts of heat are lost through the flue gas even when the excess air is controlled to a minimum value. The most effective way of recovering this heat is to install a heat exchanger at the furnace gas exit to recover heat from the flue gas. Heating combustion air is usually limited to about 400°C on a burner retrofit as above this temperature the use of an alloy steel burner and air ducting components becomes desirable. Heat exchangers are manufactured from alloy or stainless steels for gas temperatures up to 900°C. Beyond that temperature, considerably more expensive ceramic heat exchangers are required. In some situations it may be desirable to bleed air into the flue gas ahead of the heat exchanger to permit the use of the lower cost metal construction.

Heat exchangers which recover heat from the flue gas to heat the combustion air are usually called recuperators. Typical recuperators are shown in Figures 8 and 22. The heat recovered can also used to heat air for space heating, water for process use, or to generate steam in a waste heat boiler.




**Recuperator**
Figure 22

# ENERGY MANAGEMENT OPPORTUNITIES

Energy Management Opportunities is a term used to represent the ways that energy can be used wisely to save money. This section outlines a number of typical opportunities with some worked examples illustrating potential savings in energy and money. It is not a complete listing of all possible Energy Management Opportunities for furnaces, dryers, and kilns. It is intended to provide management, operating, and maintenance personnel with ideas to identify other opportunities. Worksheets have not been included because of the diverse forms of furnaces, kilns and dryers and the related energy opportunities.

Energy Management Opportunities are subdivided into Housekeeping, Low cost, and Retrofit categories.

## Housekeeping Opportunities

Implemented housekeeping opportunities are energy management actions that are done on a regular basis and never less than once a year. The following are typical Energy Management Opportunities in this category.

1. Maintain proper burner adjustments.
2. Check the excess air and combustibles in the flue gas.
3. Keep heat exchanger surfaces clean.
4. Replace or repair missing or damaged insulation.
5. Reinstall doors or covers.
6. Check furnace pressure regularly.
7. Schedule production so that each furnace operates near maximum output.

## Housekeeping Worked Examples

**1. Maintain Proper Burner Adjustments.**

It is good practice to have an experienced burner manufacturer's representative set up the burner adjustments. Furnace operators can then identify the appearance of a proper burner flame for future reference. The flame should be checked frequently, and always after any significant change in operating conditions affecting the fuel, combustion air flow, or furnace pressure.

**2. Check Excess Air and Combustibles in the Flue Gas.**

A continuous $O_2$ and Combustibles analyzer is the best arrangement, but the cost is high. Sampling tests with an Orsat or other chemical means can be a reliable guide to proper combustion conditions. Readjustment of the fuel/air ratio control should be performed promptly if required.

**3. Keep Heat Exchange Surfaces Clean.**

This is required more frequently with oil fired furnaces and, for these applications, the use of permanently installed steam or air sootblowers may be justified.

**4. Replace or Repair Missing and Damaged Insulation**

Heat radiation from a furnace with inadequate insulation can be easily detected during a walk through of the plant.

**5. Reinstall Doors or Covers.**

A 0.25 $m^2$ door is noted to be missing from a furnace operating at 900°C. Heat radiated through the opening is 400 MJ/($m^2$·h) (Figure 13). The furnace operates 4000 hours per year and fuel costs $5 per GJ.

$$\text{Annual heat loss} = 0.25\ m^2 \times 400\ MJ/(m^2 \cdot h) \times 4000h$$

$$= 400\ 000\ MJ/yr$$

$$= 400\ GJ/yr$$

$$\text{Annual savings} = \$5 \times 400$$

$$= \$2{,}000$$

This saving will be reduced slightly by the heat loss from the closed door. Some additional savings may result from the elimination of air leaking into or gas escaping from the open door.

**6. Check Furnace Pressure Regularly.**

Air leakage into or gas leakage out of a furnace can be controlled by maintaining a slight positive furnace pressure. The control damper in the furnace flue gas ducting or the related control should be readjusted if the furnace pressure is not at the correct value.

**7. Schedule Production to Operate Furnaces Near Maximum Output**

It may be possible to operate the furnace at maximum load every other day, instead of at 50 per cent load continuously. Alternatively, the work may be switched to a smaller furnace which can operate near full load continuously.

## Low Cost Opportunities

Implemented low cost opportunities are energy management actions that are done once and for which the cost is not great. The following are typical Energy Management Opportunities in this category.

1. Replace warped or damaged furnace doors and covers.
2. Install adequate monitoring instrumentation.
3. Recover heat loss to equipment cooling water.
4. Relocate the combustion air intake to recover heat within the building.

## Low Cost Worked Examples

**1. Replace Warped or Damaged Furnace Doors or Covers.**

Furnace doors or covers which are warped or damaged can be a source of considerable leakage of air into or gas out of the furnace. These should be replaced by doors or covers with tight fitting seals. Further improvement would result from installing power operators on the doors to minimize the time the doors are open, as well as make it easier for the operators.

**2. Install Adequate Monitoring Instrumentation.**

The minimum requirement is to have the ability to determine the energy used per unit of output, so that significant deviations from this can be identified and corrective action taken. The fuel or watt meter can be a portable instrument which may be used on several furnaces. Additional instrumentation would be required to identify individual losses. Measurement of flue gas temperature and oxygen content can be used to indicate flue gas loss. If a heat exchanger is used to recover heat from the flue gas, temperature measurements of the gas and air in and out of the heat exchanger can be used to check the performance.

**3. Recover Heat From Equipment Cooling Water.**

It is often possible to use the warm water discharge from equipment coolers for purposes such as process washing. In some systems the water discharge may be too cool to be useful. In these instances the installation of a water flow control valve and temperature controller may be helpful. The water flow is controlled automatically from the water temperature at the cooler outlet so that the water temperature is high enough to be useful, while maintaining proper cooling. The control system will also reduce water use.

**4. Relocate Combustion Air Intake to Recover Heat Within the Building.**

Heat generated inside the plant tends to rise, resulting in significant temperature differences between floor and ceiling. If the furnace has a forced draft fan it is often possible to install lightweight ducting from the ceiling to the fan intake. Alternatively, the ducting may be routed to an adjacent shop if considerable heat is simultaneously being generated and vented outside. Care should be taken to size the ducting adequately to minimize the pressure drop.

A furnace using 5000 kg/h of combustion air draws inside air at 20°C average temperature. Installation of a duct to the ceiling increases the average air temperature to 30°C.

$$\text{Heat recovered} = 5000 \text{ kg/h} \times (30 - 20)°\text{C} \times 1.006 \text{ kJ/(kg·°C)}$$

$$= 50\ 300 \text{ kJ/h}$$

The furnace operates for 6000 hrs per year and the fuel costs $5/GJ.

$$\text{Annual fuel savings} = \frac{50\ 300 \times 6000 \times \$5}{10^6}$$

$$= \$1{,}509 \text{ per year}$$

The cost of the ducting is $1,500.

$$\text{Simple payback} = \frac{\$1{,}500}{\$1{,}509}$$

$$= 1.0 \text{ year}$$

## Retrofit Opportunities

Implemented retrofit opportunities are energy management actions which are done once and for which the cost is significant. The following are typical Energy Management Opportunities in the retrofit category.

1. Install a heat exchanger in the flue gas outlet.
2. Reinsulate the furnace enclosure.
3. Replace the burner assembly.
4. Install a new control system.

## Retrofit Worked Examples

### 1. Install Heat Exchanger in the Flue Gas Outlet.

The cost of heat exchangers is significantly affected by the temperature of the gas entering the unit. Careful consideration should be given to introducing cold air into the gas stream, if required, to lower the gas temperature enough to use economic materials. Stainless steels or alloys cannot be used for temperatures above 950°C.

If the recovered heat is used to preheat the combustion air the burner manufacturer should be consulted to determine the maximum allowable air temperature. Frequently, this will be as low as 250°C. It is unlikely to be higher than 400°C since that would require alloy steels instead of carbon steel. If it is not practical to heat the combustion air, it may be possible to heat process water or to install a waste heat boiler to utilize the heat energy in the flue gas.

Introduction of a heat exchanger will increase the pressure drop in the flue gas system, which means that the combustion air fan capacity will be reduced. It may be necessary to install a new fan or impeller and drive motor. It is possible that the furnace pressure will be increased unless there is sufficient draft available from the stack to overcome the added resistance across the heat exchanger. Because of these and other possible complications, it is suggested that the furnace manufacturer or a consulting engineering firm be retained to make an evaluation of the proposed changes.

The economic and technical analysis that follows is based on an actual installation of high-alloy recuperators applied to an indirectly heated, continuously operating, heat-treating furnace. A custom-designed triple-pass recuperator was bolted to the exhaust leg of each of the 24 radiant tube heaters of the furnace, and each of the existing induced draft burners was replaced with a sealed positive pressure burner. The modification also included a blower system for the supply of combustion air, and improvements to the controls to reduce excess air from 15 to 20 per cent before conversion to 8 to 10 per cent. Total cost of the project was $120,000.
Before conversion, the fuel consumption per burner was measured at 193 000 kJ/h, or 4.63 GJ/h for the furnace with all burners in service. The furnace operates 6 days per week, 24 hours per day and the allowance for down time or part load operation is 15 per cent. Gas costs $4.24 per gigajoule.

$$\text{Annual fuel cost before conversion} = \frac{(100\text{-}15)}{100} \times 24 \text{ h/d} \times 6 \text{ d/wk} \times 52 \text{ w/yr} \times 4.63 \text{ GJ/h} \times \$4.24\text{/GJ}$$

$$= \$124{,}949$$

To estimate the savings, it is necessary to determine the recuperator performance. Flue gas leaves the radiant tubes at 1100°C, and enters the recuperator at this temperature. The gas leaves the recuperator at 650°C and the combustion air is heated from ambient to 500°C.

To isolate the performance of the recuperator from other savings, it is assumed that excess air before and after conversion remains at 20 per cent. The intersection of 20 per cent excess air and 1100°C on Figure 5 indicates that 64 per cent of the heat supplied in the fuel is lost in the flue gas.

$$\text{Flue gas heat loss/burner} = \frac{64}{100} \times 193\ 000$$

$$= 123\ 500 \text{ kJ/h}$$

The remainder, or 69 500 kJ/h, enters the furnace through the radiant tube.

After conversion the stack gas temperature dropped to 650°C. Using Figure 5 with 20 per cent excess air and 650°C flue gas temperature shows that 40 per cent of the heat supplied is lost, and 60 per cent enters the furnace. It is reasonable to assume that the amount of heat entering the furnace through each radiant tube does not change when a recuperator is installed, as the gas temperature leaving the tube remains at 1100°C. Sixty per cent of the heat supplied per burner after conversion, equals 69 500 kJ/h.

$$\text{Burner energy} = \frac{69\ 500}{0.6} = 115\ 800\ \text{kJ/h}$$

$$\text{Flue gas heat loss/burner} = 115\ 800 - 69\ 500$$

$$= 46\ 300\ \text{kJ/h}$$

$$\text{Energy savings} = 24\ (\text{burners}) \times (123\ 500 - 46\ 300)$$

$$= 1\ 852\ 800\ \text{kJ/h}$$

$$= 1.85\ \text{GJ/h}$$

$$\text{Savings} = \frac{1.85}{4.63} \times 100$$

$$= 40\%$$

The actual fuel consumption savings were 48 per cent. Part of the discrepancy is because of the difficulty of measuring flue gas temperatures and airflows, hence excess air quantities accurately. The modification introduced two further areas of potential savings. One of these was the improved airflow control and the resulting reduction in excess air to 8 per cent. The effect of this can also be evaluated from Figure 5 and is in the order of 2 to 3 per cent.

The second area of savings results from the changes made to the control system and this is difficult to estimate. Before conversion, burners were operated at a fixed setting and furnace temperature was controlled by turning selected burners on and off. Heat was lost from the furnace to radiant tubes not in service, because of natural convection of outside air through these tubes. This loss was eliminated with the new modulating control system.

The annual fuel savings were 48 per cent of $124,949 or about $60,000. Based on the capital cost of $120,000, the payback period for this project was 2 years.

**2. Reinsulate Furnace Enclosure.**

Older furnaces may use refractory brick for the furnace lining. If the furnace has to be rebuilt, it is frequently economical to use ceramic fibre blanket insulation. If refractory brick is required to withstand rough handling an outer layer of ceramic fibre can be used.

Since ceramic fibre is a much better insulator than refractory brick, care should be taken to ensure that the inner layer of refractory is not overheated, since its average temperature will be higher.

During a tour of a plant it is noticed that a furnace appears to be radiating substantial quantities of heat. Temperature measurements of the surface average 200°C on the walls and 250°C on the roof. The outside dimensions of the furnace are 2 m by 2 m by 6 m long. It is decided to reinsulate the furnace to give a maximum surface temperature of 50°C, to provide operator safety and heat savings.

From Figure 12, heat losses are 21.5 MJ/($m^2$·h) at 250°C, 11.6 MJ/($m^2$·h) at 200°C, and 1.7 MJ/($m^2$·h) at 50°C.

$$\text{Roof area} = 2\ \text{m} \times 6\ \text{m}$$

$$= 12\ \text{m}^2$$

$$\text{Wall area} = (2\text{m} \times 6\text{m} \times 2) + (2\text{m} \times 2\text{m} \times 2)$$

$$= 32\ \text{m}^2$$

$$\text{Heat loss before reinsulation} = [21.5\ \text{MJ/(m}^2\cdot\text{h)} \times 12\ \text{m}^2] + [11.6\ \text{MJ/(m}^2\cdot\text{h)} \times 32\ \text{m}^2]$$

$$= 692.2\ \text{MJ/h}$$

Heat loss after reinsulation $= 1.7\ MJ/(m^2 \cdot h) \times (12\ m^2 + 32\ m^2)$

$= 74.8\ MJ/h$

Note that the heat loss to the floor is not considered to be significant.

Energy savings $= 692.2 - 74.8\ MJ/h$

$= 617.4\ MJ/h$

The furnace operates 4000 hours per year, and fuel costs $5/GJ.

$$\text{Annual savings} = \frac{617.4\ MJ/h \times 4000\ h/yr \times \$5/GJ}{1000\ MJ/GJ}$$

$= \$12,348/yr$

**3. Replace Burner Assembly.**

The installation of a modern design burner assembly can permit operation at lower values of excess air, thus reducing stack losses. A new burner assembly can also be the means to provide full automation for start-up and shutdown. In a multiple burner installation automation will permit start-up and shutdown of burners to follow varying load patterns, rather than modulating the load on individual burners over a wide range. Burners generally operate more efficiently at high loads, so improvements in part load economy can be expected if some burners are shut down.

Provision should be made to shut off the combustion air to idle burners. This avoids losses due to excess air entering the furnace and not taking part in the combustion process.

**4. Install New Control System.**

Depending on the type of system presently installed it may be possible to make substantial improvements in fuel economy by upgrading the controls.

A system which operates fuel and air controls in parallel with no readjustment from measured fuel and air flows or flue gas analysis, will normally operate with higher values of excess air. Addition of flow meters for fuel and air will permit closer control under varying load conditions, permitting operation at lower values of excess air.

The addition of $O_2$ trim control of air flow compensates for variations in fuel and combustion air, and permits operation at lower levels of excess air. It should be noted that flue gas analyzers require regular maintenance and calibration. In this respect the probe type, which is located directly in the gas stream, is generally more reliable than types which require a continuous sample to be drawn from the flue gas system.

The reduction in excess air which results from the installation of an improved control system can lead to substantial savings in energy.

## APPENDICES

A — Glossary of Terms
B — Tables
C — Common Conversions

## GLOSSARY

**Absolute Temperature** — Temperature measured in degrees Kelvin. A temperature of 0°C is 273K.

**Black Body** — An object which completely absorbs all radiation falling on it and which radiates more energy at any given temperature than any other type of body.

**Combustibles** — Any gaseous constituents in the products of combustion which can burn. Carbon monoxide is the most common combustible in flue gas.

**Combustion** — The rapid chemical combination of fuel with oxygen resulting in the generation of heat.

**Emissivity** — Emissivity is the ratio of the energy radiated from a heated object to the energy radiated from a similar size black body heated to the same temperature. The value is always less than 1.0.

**Flue Gas** — The gaseous products of combustion of fuel leaving a combustion chamber.

**Heat of Vaporization** — The heat required to completely evaporate one unit of weight of a substance. Evaporate in this context means a change from liquid to vapor form, as from water to steam. Heat of vaporization is expressed as megajoules per kilogram (MJ/kg).

**Higher Heating Value** — The amount of heat produced by complete combustion of one unit of fuel, when the products of combustion are cooled to ambient temperature. The value includes the latent heat of water vapor in the products of combustion which is not normally recovered in furnace applications.

**Microprocessor** — Small computer where the main functions can be provided on a single chip.

**Orsat** — Manual flue gas analyzer which determines the quantity of carbon monoxide, carbon dioxide, and oxygen in the gas by chemical absorption.

**Oxidizing** — Oxidizing refers to the state within the furnace which promotes the formation of oxides on the surface of the product in the furnace.

**Reducing** — Reducing means a state within the furnace which converts oxides on the surface of the product in the furnace to the base metal, or prevents the formation of oxides.

**Specific Heat** — The amount of heat required to raise the temperature of one unit mass of a substance one degree of temperature. The units are usually kilojoules per kilogram per degree Celsius, $kJ/(kg \cdot {}^0C)$.

**Stoichiometric Air** — Amount of air which is theoretically required for complete combustion, with no deficiency or excess. In practice it is always necessary to provide an excess to produce complete combustion of the fuel.

**Wattmeter** — An instrument for measuring the amount of electrical power consumed, in watts or kilowatts.

## COMBUSTION AIR REQUIREMENTS

## TABLE 1

| Fuel | Stoichiometric Air kg/GJ As Fired | Typical Excess Air (Minimum) | Total Air kg/GJ As Fired |
|---|---|---|---|
| Natural Gas | 318 | 5% | 334 |
| #2 Fuel Oil | 323 | 10% | 355 |
| #6 Fuel Oil | 327 | 10% | 360 |
| Coke-Oven Gas (1) | 295 | 15% | 340 |
| Refinery Gas (2) | 312 | 10% | 343 |
| Propane | 314 | 5% | 330 |

| | | | |
|---|---|---|---|
| (1) | Analysis by volume | $CO$ | 12% |
| | | $H_2$ | 42% |
| | | $CH_4$ | 37% |
| | | $C_2H_4$ and higher | 5% |
| | | $CO_2$ | Remainder |
| (2) | Analysis by volume | $CH_4$ | 31% |
| | | $C_2H_6$ | 20% |
| | | $C_3H_8$ | 38% |
| | | $H_2$ | 5.6% |
| | | $C_4H_{10}$ and higher | 1.0% |
| | | Inert Gases | Remainder |

## TYPICAL THERMAL CONDUCTIVITY VALUES

## TABLE 2

| Material | Thermal Conductivity W/(m·°C) |
|---|---|
| Copper | 361 |
| Aluminum | 217 |
| Brass | 111 |
| Cast Iron | 40 |
| Carbon Steel | 36 |
| Low Nickel Alloy | 25 |
| High Nickel Alloy | 31 |
| Silicon Carbide | 14 |

## TYPICAL EMISSIVITY VALUES

### TABLE 3

| Material | Thermal Emissivity |
|---|---|
| Cast Iron | 0.72 |
| Carbon Steel | 0.80 |
| Low Nickel Alloy | 0.73 |
| High Nickel Alloy | 0.90 |
| Silicon Carbide | 0.90 |
| Fireclay Brick | 0.75 |
| Alumina Brick | 0.30 |

## TYPICAL SPECIFIC HEAT AND HEAT OF MELTING VALUES

### TABLE 4

| Material | Specific Heat kJ/(kg·°C) | Heat Of Melting From 0°C kJ/kg |
|---|---|---|
| Iron and Low Carbon Steel | 0.5 | 1360 |
| Aluminum | 0.92 | 1095 |
| Copper | 0.40 | 710 |
| Glass | 0.84 | Note (1) |
| Water | 4.19 | 755 |
| Zinc | 0.39 | 300 |
| Lead | 0.13 | 70 |
| Tin | 0.23 | 130 |
| Brass | 0.39 | 595 |

(1) No definite melting point.

## TYPICAL HEAT OF VAPORIZATION VALUES

## TABLE 5

| Material | Heat of Vaporization kJ/kg |
|---|---|
| Water at 20°C | 2450 |
| Tri-Chlor Ethylene | 230 |
| Acetone | 510 |
| Ethyl Alcohol | 860 |
| Iso-Propyl Alcohol | 675 |
| Benzene | 400 |
| Toluene | 350 |
| Turpentine | 290 |
| Naphtha | 240 |
| Kerosene | 200 |
| Carbon Tetrachloride | 195 |

# COMMON CONVERSIONS

| | |
|---|---|
| 1 barrel (35 Imp gal) (42 US gal) | = 159.1 litres |
| 1 gallon (Imp) | = 1.20094 gallon (US) |
| 1 horsepower (boiler) | = 9809.6 watts |
| 1 horsepower | = 2545 Btu/hour |
| 1 horsepower | = 0.746 kilowatts |
| 1 joule | = 1 N-m |
| Kelvin | = (°C + 273.15) |
| 1 kilowatt-hour | = 3600 kilojoules |
| 1 Newton | = 1 kg-m/s$^2$ |
| 1 therm | = $10^5$ Btu |
| 1 ton (refrigerant) | = 12002.84 Btu/hour |
| 1 ton (refrigerant) | = 3516.8 watts |
| 1 watt | = 1 joule/second |
| Rankine | = (°F + 459.67) |

### Cubes

| | |
|---|---|
| 1 yd$^3$ | = 27 ft$^3$ |
| 1 ft$^3$ | = 1728 in$^3$ |
| 1 cm$^3$ | = 1000 mm$^3$ |
| 1 m$^3$ | = $10^6$ cm$^3$ |
| 1 m$^3$ | = 1000 L |

### Squares

| | |
|---|---|
| 1 yd$^2$ | = 9 ft$^2$ |
| 1 ft$^2$ | = 144 in$^2$ |
| 1 cm$^2$ | = 100 mm$^2$ |
| 1 m$^2$ | = 10000 cm$^2$ |

## SI PREFIXES

| Prefix | Symbol | Magnitude | Factor |
|---|---|---|---|
| tera | T | 1 000 000 000 000 | $10^{12}$ |
| giga | G | 1 000 000 000 | $10^9$ |
| mega | M | 1 000 000 | $10^6$ |
| kilo | k | 1 000 | $10^3$ |
| hecto | h | 100 | $10^2$ |
| deca | da | 10 | $10^1$ |
| deci | d | 0.1 | $10^{-1}$ |
| centi | c | 0.01 | $10^{-2}$ |
| milli | m | 0.001 | $10^{-3}$ |
| micro | u | 0.000 001 | $10^{-6}$ |
| nano | n | 0.000 000 001 | $10^{-9}$ |
| pica | p | 0.000 000 000 001 | $10^{-12}$ |

# UNIT CONVERSION TABLES
## METRIC TO IMPERIAL

| FROM | SYMBOL | TO | SYMBOL | MULTIPLY BY |
|---|---|---|---|---|
| amperes/square centimetre | $A/cm^2$ | amperes/square inch | $A/in^2$ | 6.452 |
| Celsius | °C | Fahrenheit | °F | (°C × 9/5) + 32 |
| centimetres | cm | inches | in | 0.3937 |
| cubic centimetres | $cm^3$ | cubic inches | $in^3$ | 0.06102 |
| cubic metres | $m^3$ | cubic foot | $ft^3$ | 35.314 |
| grams | g | ounces | oz | 0.03527 |
| grams | g | pounds | lb | 0.0022 |
| grams/litre | g/L | pounds/cubic foot | $lb/ft^3$ | 0.06243 |
| joules | J | Btu | Btu | $9.480 \times 10^{-4}$ |
| joules | J | foot-pounds | ft-lb | 0.7376 |
| joules | J | horsepower-hours | hp-h | $3.73 \times 10^{-7}$ |
| joules/metre, (Newtons) | J/m, N | pounds | lb | 0.2248 |
| kilograms | kg | pounds | lb | 2.205 |
| kilograms | kg | tons (long) | ton | $9.842 \times 10^{-4}$ |
| kilograms | kg | tons (short) | tn | $1.102 \times 10^{-3}$ |
| kilometres | km | miles (statute) | mi | 0.6214 |
| kilopascals | kPa | atmospheres | atm | $9.87 \times 10^{-3}$ |
| kilopascals | kPa | inches of mercury (@ 32°F) | in Hg | 0.2953 |
| kilopascals | kPa | inches of water (@ 4°C) | in $H_2O$ | 4.0147 |
| kilopascals | kPa | pounds/square inch | psi | 0.1450 |
| kilowatts | kW | foot-pounds/second | ft-lb/s | 737.6 |
| kilowatts | kW | horsepower | hp | 1.341 |
| kilowatt-hours | kWh | Btu | Btu | 3413 |
| litres | L | cubic foot | $ft^3$ | 0.03531 |
| litres | L | gallons (Imp) | gal (Imp) | 0.21998 |
| litres | L | gallons (US) | gal (US) | 0.2642 |
| litres/second | L/s | cubic foot/minute | cfm | 2.1186 |
| lumen/square metre | $lm/m^2$ | lumen/square foot | $lm/ft^2$ | 0.09290 |
| lux, lumen/square metre | lx, $lm/m^2$ | footcandles | fc | 0.09290 |
| metres | m | foot | ft | 3.281 |
| metres | m | yard | yd | 1.09361 |
| parts per million | ppm | grains/gallon (Imp) | gr/gal (Imp) | 0.07 |
| parts per million | ppm | grains/gallon (US) | gr/gal (US) | 0.05842 |
| permeance (metric) | PERM | permeance (Imp) | perm | 0.01748 |
| square centimetres | $cm^2$ | square inches | $in^2$ | 0.1550 |
| square metres | $m^2$ | square foot | $ft^2$ | 10.764 |
| square metres | $m^2$ | square yards | $yd^2$ | 1.196 |
| tonne (metric) | t | pounds | lb | 2204.6 |
| watt | W | Btu/hour | Btu/h | 3.413 |
| watt | W | lumen | lm | 668.45 |

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# UNIT CONVERSION TABLES
# IMPERIAL TO METRIC

| FROM | SYMBOL | TO | SYMBOL | MULTIPLY BY |
|---|---|---|---|---|
| ampere/$in^2$ | $A/in^2$ | ampere/$cm^2$ | $A/cm^2$ | 0.1550 |
| atmospheres | atm | kilopascals | kPa | 101.325 |
| British Thermal Unit | Btu | joules | J | 1054.8 |
| Btu | Btu | kilogram-metre | kg-m | 107.56 |
| Btu | Btu | kilowatt-hour | kWh | $2.928 \times 10^{-4}$ |
| Btu/hour | Btu/h | watt | W | 0.2931 |
| calorie, gram | cal or g-cal | joules | J | 4.186 |
| chain | chain | metre | m | 20.11684 |
| cubic foot | $ft^3$ | cubic metre | $m^3$ | 0.02832 |
| cubic foot | $ft^3$ | litre | L | 28.32 |
| cubic foot/minute | cfm | litre/second | L/s | 0.47195 |
| cycle/second | c/s | Hertz | Hz | 1.00 |
| Fahrenheit | °F | Celsius | °C | (°F-32)/1.8 |
| foot | ft | metre | m | 0.3048 |
| footcandle | fc | lux, lumen/ square metre | lx, $lm/m^2$ | 10.764 |
| footlambert | fL | candela/square metre | $cd/m^2$ | 3.42626 |
| foot-pounds | ft-lb | joule | J | 1.356 |
| foot-pounds | ft-lb | kilogram-metres | kg-m | 0.1383 |
| foot-pounds/second | ft-lb/s | kilowatt | kW | $1.356 \times 10^{-3}$ |
| gallons (Imp) | gal (Imp) | litres | L | 4.546 |
| gallons (US) | gal (US) | litres | L | 3.785 |
| grains/gallon (Imp) | gr/gal (Imp) | parts per million | ppm | 14.286 |
| grains/gallon (US) | gr/gal (US) | parts per million | ppm | 17.118 |
| horsepower | hp | watts | W | 745.7 |
| horsepower-hours | hp-h | joules | J | $2.684 \times 10^6$ |
| inches | in | centimetres | cm | 2.540 |
| inches of Mercury (@ 32°F) | in Hg | kilopascals | kPa | 3.386 |
| inches of water (@ 4°C) | in $H_2O$ | kilopascals | kPa | 0.2491 |

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# UNIT CONVERSION TABLES
## IMPERIAL TO METRIC (cont'd)

| FROM | SYMBOL | TO | SYMBOL | MULTIPLY BY |
|---|---|---|---|---|
| lamberts | * L | candela/square metre | $cd/m^2$ | 3.183 |
| lumen/square foot | $lm/ft^2$ | lumen/square metre | $lm/m^2$ | 10.76 |
| lumen | lm | watt | W | 0.001496 |
| miles (statute) | mi | kilometres | km | 1.6093 |
| ounces | oz | grams | g | 28.35 |
| perm (at 0°C) | perm | kilogram per pascal-second-square metre | $kg/Pa\text{-}s\text{-}m^2$ (PERM) | $5.721 \times 10^{-11}$ |
| perm (at 23°C) | perm | kilogram per pascal-second-square metre | $kg/Pa\text{-}s\text{-}m^2$ (PERM) | $5.745 \times 10^{-11}$ |
| perm-inch (at 0°C) | perm. in. | kilogram per pascal-second-metre | kg/Pa-s-m | $1.4532 \times 10^{-12}$ |
| perm-inch (at 23°C) | perm. in. | kilogram per pascal-second-metre | kg/Pa-s-m | $1.4593 \times 10^{-12}$ |
| pint (Imp) | pt | litre | L | 0.56826 |
| pounds | lb | grams | g | 453.5924 |
| pounds | lb | joules/metre, (Newtons) | J/m, N | 4.448 |
| pounds | lb | kilograms | kg | 0.4536 |
| pounds | lb | tonne (metric) | t | $4.536 \times 10^{-4}$ |
| pounds/cubic foot | $lb/ft^3$ | grams/litre | g/L | 16.02 |
| pounds/square inch | psi | kilopascals | kPa | 6.89476 |
| quarts | qt | litres | L | 1.1365 |
| slug | slug | kilograms | kg | 14.5939 |
| square foot | $ft^2$ | square metre | $m^2$ | 0.09290 |
| square inches | $in^2$ | square centimetres | $cm^2$ | 6.452 |
| square yards | $yd^2$ | square metres | $m^2$ | 0.83613 |
| tons (long) | ton | kilograms | kg | 1016 |
| tons (short) | tn | kilograms | kg | 907.185 |
| yards | yd | metres | m | 0.9144 |

* "L" as used in Lighting

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The following typical values for conversion factors may be used when actual data are unavailable. The MJ and Btu equivalencies are heats of combustion. Hydrocarbons are shown at the higher heating value, wet basis. Some items listed are typically feedstocks, but are included for completeness and as a reference source. The conversion factors for coal are approximate since the heating value of a specific coal is dependent on the particular mine from which it is obtained.

| ENERGY TYPE | METRIC | IMPERIAL |
|---|---|---|
| COAL | | |
| — metallurgical | 29,000 megajoules/tonne | $25.0 \times 10^6$ Btu/ton |
| — anthracite | 30,000 megajoules/tonne | $25.8 \times 10^6$ Btu/ton |
| — bituminous | 32,100 megajoules/tonne | $27.6 \times 10^6$ Btu/ton |
| — sub-bituminous | 22,100 megajoules/tonne | $19.0 \times 10^6$ Btu/ton |
| — lignite | 16,700 megajoules/tonne | $14.4 \times 10^6$ Btu/ton |
| COKE | | |
| — metallurgical | 30,200 megajoules/tonne | $26.0 \times 10^6$ Btu/ton |
| — petroleum | | |
| — raw | 23,300 megajoules/tonne | $20.0 \times 10^6$ Btu/ton |
| — calcined | 32,600 megajoules/tonne | $28.0 \times 10^6$ Btu/ton |
| PITCH | 37,200 megajoules/tonne | $32.0 \times 10^6$ Btu/ton |
| CRUDE OIL | 38,5 megajoules/litre | $5.8 \times 10^6$ Btu/bbl |
| No. 2 OIL | 38.68 megajoules/litre | $5.88 \times 10^6$ Btu/bbl<br>$.168 \times 10^6$ Btu/IG |
| No. 4 OIL | 40.1 megajoules/litre | $6.04 \times 10^6$ Btu/bbl<br>$.173 \times 10^6$ Btu/IG |
| No. 6 OIL (RESID. BUNKER C) | | |
| @ 2.5% sulphur | 42.3 megajoules/litre | $6.38 \times 10^6$ Btu/bbl<br>$.182 \times 10^6$ Btu/IG |
| @ 1.0% sulphur | 40.5 megajoules/litre | $6.11 \times 10^6$ Btu/bbl<br>$.174 \times 10^6$ Btu/IG |
| @ .5% sulphur | 40.2 megajoules/litre | $6.05 \times 10^6$ Btu/bbl<br>$.173 \times 10^6$ Btu/IG |
| KEROSENE | 37.68 megajoules/litre | $.167 \times 10^6$ Btu/IG |
| DIESEL FUEL | 38.68 megajoules/litre | $.172 \times 10^6$ Btu/IG |
| GASOLINE | 36.2 megajoules/litre | $.156 \times 10^6$ Btu/IG |
| NATURAL GAS | 37.2 megajoules/$m^3$ | $1.00 \times 10^6$ Btu/MCF |
| PROPANE | 50.3 megajoules/kg<br>26.6 megajoules/litre | $.02165 \times 10^6$ Btu/lb<br>$.1145 \times 10^6$ Btu/IG |
| ELECTRICITY | 3.6 megajoules/kWh | $.003413 \times 10^6$ Btu/kWh |